5. Carbon Monoxide

Effects of carbon monoxide on human health heave been investigated almost entirely by toxicological experiments and clinical observations in conjunction with occupational exposure (e.g., of parking attendants, tunnel and toll plaza personnel). Epidemiological studies of carbon monoxide have looked also at oxidants (because of the relation of both to auto exhaust) and other pollutants.

Hexter and Goldsmith (1971) found a significant association between daily mortality in Los Angeles County and levels of carbon monoxide, but no significant association between mortality and oxidant levels. An increase in carbon monoxide level from 7.3 ppm (lowest 24-hour basin average observed during the study period) to 20.2 ppm (highest observed) was eleven deaths for that day. Because the analysis was controlled only for temperature, leaving out other possibly relevant factors, the results should be viewed with caution.

Clinical studies by Aronow et al. (1972, 1973, 1974) have associated carbon monoxide with onset of angina during severe exercise and intermittent claudication. These studies do not yield useful dose-effect functions, but provide supportive evidence.

6. Other Pollutants

Several useful investigations were conducted on the effects of other pollutants or non-specific air pollution. These include a study of the effects of benzo(a)pyrene by Carnow and Meier and of the effects of non-specific air pollution on university students.

A study by Carnow and Meier (1973) of lung cancer mortality in the 48 contiguous United States and in 19 countries concluded that an increase of 1 μg of benzo(a)pyrene in 1000 m^3 of air was associated with an increase of 5 percent in lung cancer mortality. Benzo(a)pyrene levels were estimated on the basis of fuel consumption, rather than direct measurements. This casts strong doubt on the validity of the results.

Durham (1974) investigated the health effects of air pollution on student populations at seven California universities. He controlled for climatic variables and socioeconomic characteristics, as well as confounding factors, such as chronic conditions, prescheduled appointments, weekends, holidays, and exam periods. The data suggest that a 16.7 percent excess in respiratory illness in the form of sore throat, pharyngitis, and tonsillitis among students at University of Southern California over students at University of California at Irvine may have been due to levels of nitric oxide, nitrogen dioxide, and sulfur dioxide that were 3-4 times as high. The similar incidence of common cold symptoms and eye irritation was attributed to the similar levels of photochemical oxidants. No such strong associations between respiratory illness and pollution were found for schools in the San Francisco Bay area.

A report by the California Air Resources Board (Leung et al., 1975) presents a series of dose-effect functions representing the health effects of oxidants, nitrogen dioxide, and carbon monoxide. These were developed on the basis of questionnaires completed by a panel of 14 experts for three age groups and 11 pre-existing disease conditions. The results are of some interest as an expert consensus, but the most significant outcome was the experts' own assessment that, because of lack of adequate data, their judgment was "not trustworthy" in 40 percent of the oxidant, 82 percent of the carbon monoxide, and 92 percent of the nitrogen dioxide values. This lack of confidence by a panel of recognized experts in estimating health effects of various levels of pollution is a salutory reminder that the art of developing dose-effect functions to human health is a long way from being an exact science.

B. DAMAGE TO VEGETATION

The effects of air pollutants on crops and ornamental plants has been the subject of numerous, but inconsistent, investigations. These are surveyed here under the five major pollutants: sulfur dioxide, oxidants, nitrogen oxides, acid rain, and fluorides. Some general remarks about vegetation dose-effect functions precede the survey.

1. General Remarks

Concern over air pollution damage to vegetation has received renewed impetus from the recent discovery of heretofore unsuspected high oxidant levels in rural areas and the completion of investigations indicating substantial crop losses at these levels. The more significant investigations of air pollutant damage to vegetation are listed in Table 9, which specifies the pollutant, plant, type of effect, and author reference. The recent date of these discoveries points up several basic flaws in the studies of vegetation damage, which are delineated briefly here and discussed at greater length in Chapter III (Analytical Methodology).

The principal problems and issues in the development of dose-effect functions in this area are analogous to those encountered for health effects and material damage, but there are significant differences. These are discussed below in terms of:

- Types of studies
- Determination of exposure
- Determination of effect
- Presentation of results

Investigations of the effects of air pollutants on vegetation have been designed primarily to determine susceptibilities of individual plant varieties, rather than to establish a broadly applicable relationship between dose and effect. Consequently, there has been relatively little interest in coordinating the research effort or in setting uniform standards and conditions of investigation that would permit some aggregation or comparison of the results of different studies.

Table 9. Selected Studies of Vegetation Effects of Major Air Pollutants

Pollutant	Plant	Effect	Reference
SO_2	Ryegrass	Leaf senescence	Bleasdale, 1973
SO_2	Lichens and mosses	Death	Mansfield & Bull, 1972
SO_2	Soybeans	Yield reduction	Davis, 1972
SO_2	Poplar	Leaf injury	Dochinger, 1972
SO_2	4 ornamental tree species	Leaf necrosis	Temple, 1972
SO_2, NO_2	87 native desert species	Leaf injury	Hill et al., 1974
SO_2, NO_2	6 crop plant species	Leaf injury	Tingey et al., 1971
SO_2, O_3	Tobacco	leaf injury	Menser & Heggestad, 1966
SO_2, O_3	White pine	Needle injury	Linzon, 1966
Acid rain	Tomato	Yield reduction	Kratky et al., 1974
Acid mist	Yellow birch	Growth reduction	Wood & Borman, 1971
O_3	Tobacco	Leaf fleck	Heck et al., 1966
O_3	Tobacco	Leaf fleck	Turner et al., 1972
O_3	Conifers	Needle injury	Davis & Wood, 1972
O_3	Pine	Photosynthesis reduction	Botkin et al., 1971
O_3	Pine	Photosynthesis reduction	Barnes, 1972
O_3	White pine	Needle injury	Costonis & Sinclair, 1969
O_3	Ponderosa pine	Needle injury and tree death	Miller, 1973
O_3	Geranium, carnation	Reduction or delay af flower development	Feder, 1970, 1972, 1973
O_3	35 crap and ornamental species	Leaf injury	Heck & Tingey, 1971
O_3	Poinsettia	Reduction or delay of bract development	Feder et al 1972, 1973
O_3, PAN	Navel orange	Increased fruit drop	Thompson et al., 972
PAN	Navel organge	Growth reduction and leaf drop	Thompson & Kats, 1975
O_x	Tobacco	Leaf fleck	Heagle and Heck, 7973
O_x	Potatoes	Yield reduction	Heggestad, 1973
O_x	Cotton	Yield reduction	Brewer & Ferry, 1974
O_x	Corn	Yield and growth reduction	Feder, 1972, 1973
O_x	Corn	Yield reduction	Thompson, 1975
O_x	Spinach, radish, lettuce	Yield reduction	Thompson, 1975
O_x	Lemons	Yield reduction	Thompson & Taylor, 1969
NO_2	Bean, tomato, tobacco	Weight and chlorophyll reduction	Taylor & Eaton, 1966
NO_2	Navel orange	No significant effect	Thompson et al. 1971
NO_2	Pine and yellow poplar	Growth reduction	Stone & Skelly, 1974
NO_2, F^-	Citrus trees	Yield reduction	Thompson & Taylor, 1969
F^-	Tomato, gladiolus, corn, conifers, citrus, alfalfa, sorghum	Leaf injury, yield reduction	McCune, 1969
F^-	Soybeans	Leaf injury, transpiration reduction	Wiebe & Poovaiah, 1973, Poovaiah & Wiebe 1973

The principal pollutants implicated in substantial damage to vegetation are sulfur dioxide, oxidants, nitrogen oxides, acid rain (probably a dilute solution of sulfuric, nitric, and hydrochloric acids), and fluorides. The determination of response of crops and forests is severely handicapped by the virtual lack of monitoring stations in rural areas. Consequently, ambient levels are determined on the basis of daring interpolations, between levels at distant stations or occasional measurements with the aid of portable instruments.

In the past, determination of effects was based largely on measurement of the extent of leaf injury and several indices were developed relating this measure to yield loss. Leaf injury is still considered an important indication of effect in certain plants, such as lettuce and tobacco, because leaf appearance affects saleability. However, substantial losses of fruit, grain, and timber have been found even in the absence of significant leaf injury, so the latter can no longer serve as an indiscriminate proxy for yield loss. An additional undetermined amount of yield loss occurs when more resistant plant varieties are substituted for the more susceptible ones, which tend to be more productive.

Effects of air pollutants on vegetation exhibit wide variations among the various species and as a result of differing genetic and environmental conditions. The latter include stage of growth, general viability and vigor, temperature, humidity, amount of insolation, soil moisture and acidity, and availability of nutrients. These are much more important here than in the case of human health effects, where the target population belongs to one species and genetic and environmental conditions are controlled within a more narrow range.

Most applications of dose-effect functions in the decision-making process require aggregation of effect measures over large target popu-tions and geographic areas. Efforts to satisfy these requirements have been frustrated largely by the wide variations of study results and by their basic incomparability, which was mentioned earlier. There have been some attempts to alleviate the problem through the construction of data envelopes and/or scatter diagrams, which provide a very gross indication of the direction and order of magnitude of the effect as a function of exposure.

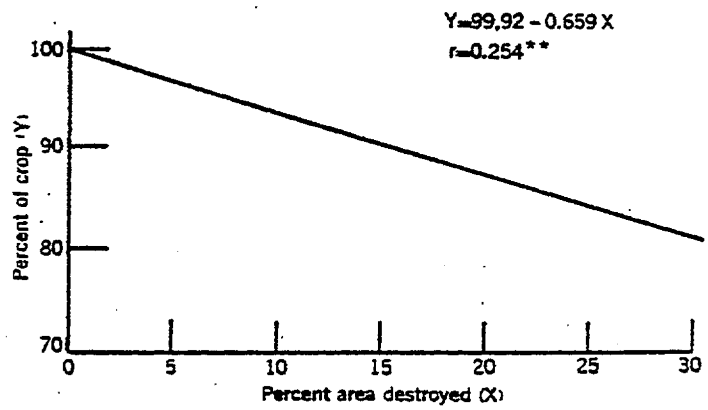
In conclusion, the state of development of consistent and broadly applicable dose-effect functions relating exposure to air pollutants with vegetation damages is considerably less advanced than that in the areas of health effects or materials damages. The major reasons are the scarcity of air quality records in rural areas, some lack of foresight and coordination in the design of investigations and presentation of results, but most of all the broad variety of target species and the ensuing variability of effects.

2. Sulfur Oxides

Early studies identified sulfur dioxide as the primary factor in air pollution damage to vegetation, and many of these have developed quantitative relationships between SO_2 levels and plant injury, or yield loss. More recent investigations have examined the effects of acid rain and mist. Dose-effect functions of single plant species have been investigated for ryegrass (Bleasdale, 1973), soybean (Davis, 1972), and poplar (Dochinger, 1972). More diversified studies have focussed on ornamentals (Temple, 1972), mosses and lichens (Mansfield and Bull, 1972), and a variety of desert species (Hill et al., 1974).

Exposure of ryegrass to sulfur dioxide in coal smoke was found to reduce plant weight between 16 and 57 percent (Bleasdale, 1973). Earlier leaf senescence was also observed in plants exposed to ambient SO_2. The reliability of the SO_2 data is in question due to the imprecise measurement of ambient pollutants. Moreover, the coal smoke may well contain various particulate fractions capable of producing damage.

The relationship between leaf injury and yield loss has been investigated by Davis (1972) in a three-year study involving 485 plots of soybeans. Sulfur dioxide fumigations were carried out at two growth stages during the first two years, and at seven growth stages during the last year. A strong correlation was found between leaf area destroyed and reduction of yield (see Figure 10). However, no direct link has been established between SO_2 concentration and yield, though there are indications that the raw data could provide this information.

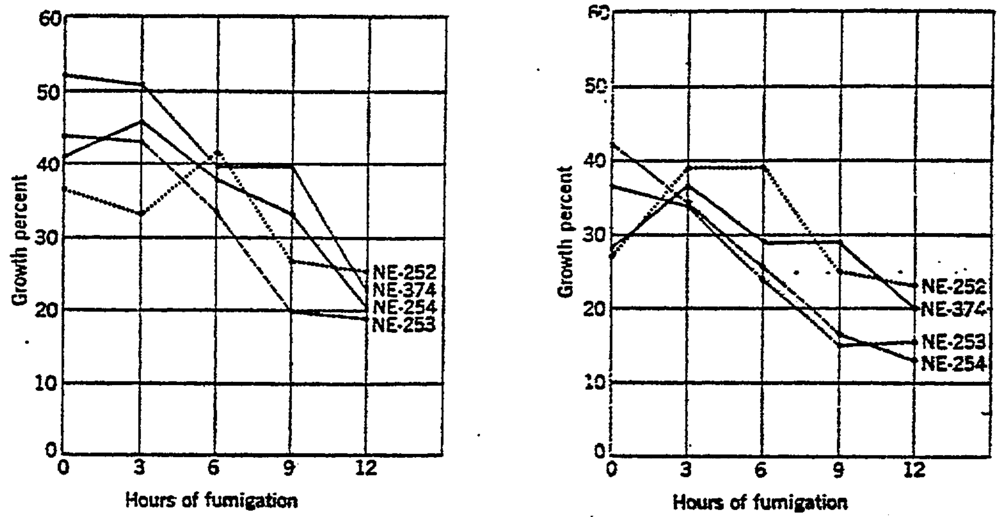


Source: Davis, 1972

Figure 10. Correlation of Soybean Yield with Leaf Area Destroyed

The effect of sulfur dioxide fumigation on a special variety of hybrid poplar was documented by Dochinger et al. (1972). Fumigation was carried out at 5 ppm for 0, 3, 6, 9, and 12 hours in controlled environment chambers. Results were plotted as percent leaf injury vs. hours of fumigation for both lower and upper shoots and various clonal variations within the species (see Figure 11). The results provide a good damage function at fixed concentration, but the extension to other concentrations and the applicability to other species is very limited.

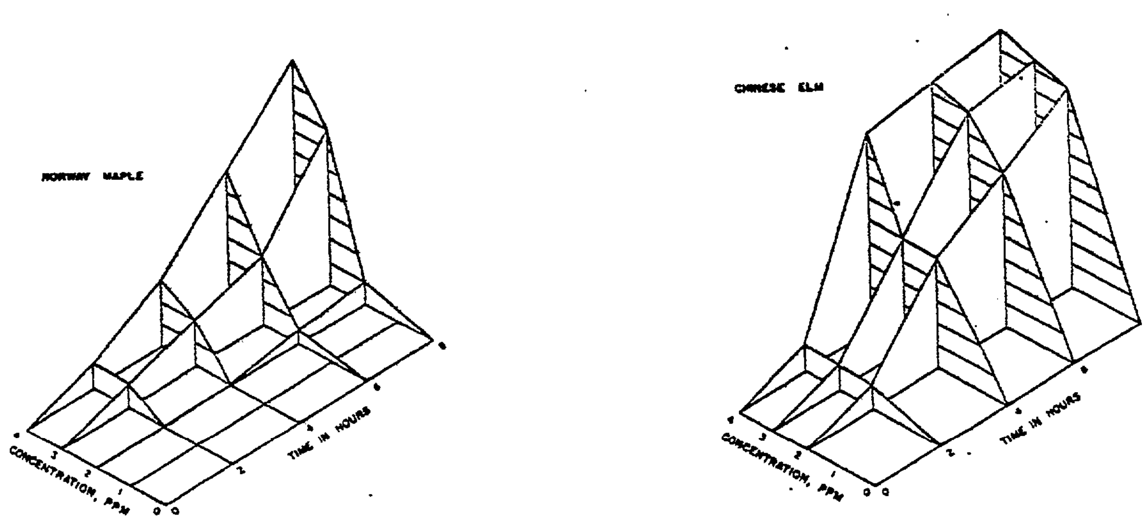
Air pollution may cause substantial damage to ornamental plants, leafy vegetables, and native vegetation through foliar injury alone. Ornamentals are used for their aesthetic value and hence, deterioration in plant appearance reduces its saleability. Native species may not have an assigned economic value, but destruction of their foliage is likely to reduce aesthetic enjoyment or to produce increased erosion.



Source: Dochinger <u>et al.</u>, 1972

Figure 11. Relationship Between Length of Exposure to SO_2 and Growth of Upper (left} and Lower (right) Shoots for Various Poplar Clones

Effects of sulfur dioxide exposure of four species of ornamental trees were investigated by Temple (1972) with the aid of controlled environmental chambers. Some results are plotted in Figure 12 in the form of a three-dimensional surface representing degree of leaf necrosis as a function of both time and concentration. Accuracy of the results is within 5-10 precent.



Source: Temple, 1972

Figure 12. Three-Dimensional Relationship Between Exposure to SO_2 and Leaf Necrosis in Norway Maple and Chinese Elm

In a massive study of the effects of power plant emissions on native vegetation, Mansfield and Bull (1972) found that lower plant types, such as lichens and mosses, suffer extensive damage or death at SO_2 concentrations as low as 0.01 ppm. This is due to the concentration of toxic substances in the plant tissue over long periods of time, coupled with the fact that these plants take up airborne substances to support a portion of their nutrient requirements.

Hill et al. (1974) fumigated some 80 species of desert plants with sulfur dioxide and a combination of SO_2 and NO_2 in portable environmental chambers. Most of the species were found to be resistant to two-hour exposures at concentrations up to 2 ppm, but some foliar injury appeared at higher levels up to 7 ppm. Moreover, no synergistic effect was observed at the levels used.

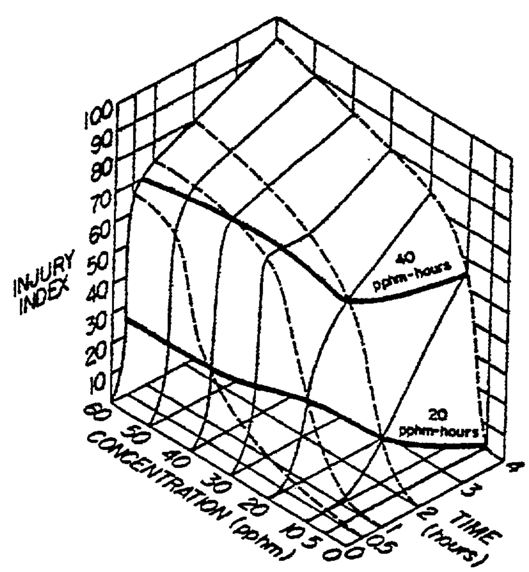
Investigations of SO_2 injury to white pine near a smelter were coupled with ozone fumigation to determine whether either pollutant was responsible (Linzon, 1966). Exposures to SO_2 levels of 0.25 ppm for several hours were found to cause injury, as were O_3 concentrations of 0.60 ppm for 2-4 hours. The combined effect of these pollutants, however, was not investigated carefully.

On the other hand, distinct synergistic effects have been observed upon exposure of tobacco to acute fumigations with both SO_2 and O_3 (Menser and Heggestad, 1966). Three cultivars of tobacco showed no leaf damage upon exposure to 2-4 hours of 0.03 ppm O_3 levels and 0.24 ppm SO_2. However, when these concentrations were used together, 38 percent of the leaf area suffered damage after a 2-hour fumigation and 75 percent after a 4-hour fumigation. The corresponding leaf areas damaged were 15 and 41 percent, respectively.

3. Oxidants

Effects of photochemical oxidants, including ozone, have attracted a great deal of attention, especially in the wake of the recent discovery of high oxidant levels in rural areas. Most investigations have been directed at field crops, such as alfalfa, broccoli, clover, corn, cotton, cucumbers, lettuce, oats, potatoes, radishes, sorghum, spinach, tobacco, and tomatoes (Heck et al., 1966; Heck and Tingey, 1971; Feder, 1973; Turner et al., 1972; Heggestad, 1973; Heagle and Heck, 1974; Brewer and Ferry, 1974; Thompson, 1975). Other studies dealt with citrus trees (Thompson and Taylor, 1969; Thompson et al., 1972; Thompson and Kats, 1975), coniferous lumber trees (Costonis and Sinclair, 1969; Botkin et al., 1971; Barnes, 1972; Davis and Wood, 1972; Miller, 1973), and such ornamental plants as carnations, geraniums, and poinsettias (Feder, 1970; Feder, 1973; Feder et al., 1972).

The first major crop plant to be investigated was the experimental and highly susceptible Bel W-3 tobacco cultivar. Heck et al. (1966) showed that varying exposures of up to 60 ppm of ozone for four hours may cause more than 90 percent leaf injury. The results were plotted in a three-dimensional surface representing an injury index as a function of both exposure time and concentration (see Figure 13).



Source: Heck et al., 1966

Figure 13. Three-Dimensional Relationship Between Exposure to Ozone and Injury to Bel W-3 Tobacco

Turner et al. (1972) assessed directly ozone damage to tobacco by measuring height, dry weight, leaf area, amount of fleck injury, as well as total leaf stomatal conductance, an indirect measure of photosynthesis and respiration. Four cultivars of varying sensitivity were grown under field conditions during both years of the study and in greenhouses during the second year. The air quality data specifies both diurnal variations and daily peak oxidant readings throughout the growing season. The uninjured leaf area for the most tolerant (6524) and the most sensitive (Bel W-3) cultivars was determined to be 10 and 71 percent, respectively, in the presence of ozone, and 10 and 14 percent, respectively, in filtered air. Standard errors are reported for most of the results.

The predisposition to injury from previous exposure was investigated by Heagle and Heck (1974), again for the Bel W-3 cultivar. Plants exposed to seven days of continuous high oxidant levels exhibited more than twice as much injury as the total of seven plants exposed for only one day each. The postulated mechanisms for the cumulative injury are progressive accumulations of toxic substances, progressive degradation of cell membranes, or a gradual disruption of enzyme processes. The eight week mean total injury per leaf indices were found to be twice as high for continuous groups as for daily exposure groups.

In a similar set of experiments, Heck and Tingey (1971) obtained acute injury indices as a function of exposure time and concentration for a number of crop and ornamental plants. The plants were exposed to .075 - 1.0 ppm ozone levels for periods of up to seven hours. Typical results for the more important varieties are shown in Table 10.

Table 10. Ozone Injury to Selected Plants

	Injury Index											
	1.0 hr				2.0 hr				4.0 hr			
Plants	7.5 pphm	15 pphm	30 pphm	60 pphm	7.5 pphm	15 pphm	30 pphm	60 pphm	7.5 pphm	15 pphm	30 pphm	60 pphm
Tomato, Roma	>1	19	63	—	1	52	91	—	10	38	93	—
Broccoli, Calabrese	2	>1	15	—	0	3	61	—	0	2	66	—
Spinach, Northland	0	0	1	—	0	0	25	—	0	3	77	—
Sorghum, Martin	—	>1	7	59	—	4	48	78	—	36	44	96
Red Clover, Pennscott	—	1	7	41	—	0	38	60	—	16	29	84
Cucumber, Long Marketer	—	0	2	18	—	0	6	9	—	1	7	18

Source: Heck and Tingey, 1971.

Potatoes have exhibited up to 50 percent reduction in yield in Maryland upon exposure to oxidant levels above 0.05 ppm. Heggestad (1973) has reported on a number of potato cultivars, with yields of the Haig and Norland varieties being reduced most significantly. These yield losses were shown to be at least qualitatively related to leaf injury.

Effects of oxidant exposure on cotton yield in the San Joaquin Valley were studied during a two-year period in four locations by Brewer and Ferry (1974). Cotton grown in filtered air was found to produce 10-30 percent more yield than control plants grown in chambers containing unfiltered air or those grown on the outside (see Table 11).

Table 11. Effects of Oxidants on Cotton Yield

Location	Plot	1972 Yields		1973 Yields	
		Bolls/ plant	Wt. of lint & seed	Bolls/ plant	Wt. of lint & seed
			gm		gm
Parlier	Outside	7.5	58.6	10.2	44.1
	Ambient air	7.6	55.3	8.6	55.7
	Filtered air	9.5	68.3	12.4	78.6
Hanford	Outside	15.0	101.8	9.4	65.5
	Ambient air	14.6	99.0	7.4	47.5
	Filtered air	18.8	124.3	9.5	58.3
Five Points	Outside	11.1	75.3	12.2	83.7
	Ambient air	11.0	76.9	9.8	63.9
	Filtered air	12.7	82.9	10.9	67.2
Cotton Center	Outside	...	...	8.2	49.3
	Ambient air	...	...	6.0	30.7
	Filtered air	...	...	7.5	41.0

Source: Brewer and Ferry, 1974

Effect on corn yield has been studied in New England (Feder, 1972) and in California (Thompson, 1975). Feder found that corn exposed to pollutant levels of approximately 0.10 ppm for seven hours per day, five days per week, suffers a reduction of 30 percent in leaf area, 20 percent in stem length, 32 percent in ear weight, and 60 percent in number of filled kernels per ear. Thompson reported significant yield reductions for two cultivars of corn. In the case of Monarch Advance, a susceptible variety, fresh weight per husked ear was reduced by 28 percent by exposure to ambient smog over the growing season. For Bonanza corn, a more resistant variety, ear weight was only slightly affected, but the number of second ears was reduced by 75 percent when compared with plants grown in filtered air. Other effects of the controlled greenhouses may have accounted for a portion of the yield reduction.

Thompson (1975) also found major reductions in plant weight for spinach, radish, and lettuce grown under varying concentrations of photochemical smog. The results are reported in Table 12.

Table 72. Yield of Several Vegetables Exposed to Various Levels of Photochemical Smog

Index Ambient Smog	Spinach Plant wt. (grams)	Spinach Percent	Radish Plant wt. (grams)	Radish Percent	Lettuce Plant wt. (grams)	Lettuce Percent
0	37.1	100	8.4	100	549	100
25	38.6	104	8.8	104	525	96
50	31.6	85	7.7	92	491	89
75	31.8	86	7.2	86	401	73
100	18.6	50	5.2	62	317	58

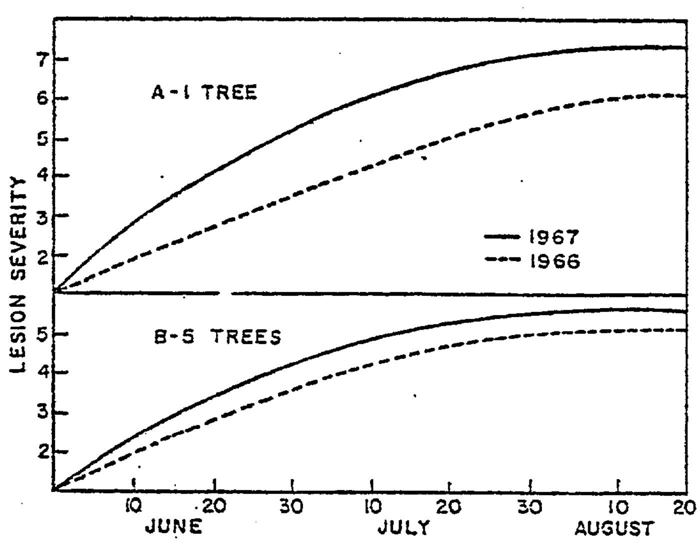
Source: Thompson, 1975

The yield of lemons was found to be significantly affected by ozone and nitrogen dioxide in ambient smog, but the effect of component pollutants was not adequately isolated (Thompson and Taylor, 1969). In a similar fashion, exposure of navel orange trees to both ozone and peroxyacetyl nitrate have shown that ozone alone causes little damage, but peroxyacetyl nitrate and photochemical smog produce significant increases in fruit drop.

The most extensive survey of the effects of oxidants on coniferous trees has been performed by Davis and Wood (1972). The study focused on leaf injury to new growth in 2-6 year-old seedlings, which may affect the photosynthesis process, and hence, the eventual growth of the trees. Six species of pine (Pinus), two of larch (Larix), and eastern hemlock (Tsuga canadensis) were found to be susceptible to 8-hour exposures to 0.25 ppm ozone levels every two weeks. Nine other coniferous species including four spruce (Picea), two fir (Abies), Douglas fir (Pseudotsuga menzesii), Aborvitae (Tsuga occidentalis), and red pine (Pinus resinosa) were found to be resistant to damage at these levels.

Studies measuring photosynthesis more directly in three species of yellow pine have been performed by Botkin et al. (1971) and Barnes (1972). Barnes' results indicate that photosynthesis is sometimes enhanced at ozone levels up to 5 pphm, but extended exposures to 15 pphm levels reduces CO_2 exchange in most cases. Botkin, on the other hand, found that much higher doses in experimental chambers had no significant effects in producing either visible symptoms or reduction of photosynthesis.

Costonis and Sinclair (1969) investigated ozone injury to white pine (Pinus strobus L.) in both controlled environment and portable polyethelene chambers. More significant in terms of extended injury were their field measurements on development of symptoms over a two-year period. Highest four-hour mean ozone concentrations varied from 0.044 to 0.052 ppm in 1966 and 0.05 - 0.086 ppm in 1967. Corresponding injury manifested by necrotic lesions on the needles and measured on a scale of 1-8 are shown in Figure 14 for a single highly susceptible tree (A) and five normal trees (B).



Source: Costonis and Sinclair, 1969.

Figure 14. Ozone Injury to White Pine Needles as a Function of Time for Two Years with Different Ozone Levels for a Single Susceptible (A) and Five Normal (B) Trees.

Ozone damage to Ponderosa pine was studied by Miller (1973) in the San Bernardino National Forest. The trees suffered an 8 percent mortality rate over a three-year period as compared to a normal rate of less than 3 percent. They finally succumbed to attack by bark beetles after being weakened by ozone.

Carnation, geranium, and poinsettia cultivars have all been found susceptible to damage by ozone (Feder, 1970; Feder et al., 1972; Feder, 1972). Plants grown to maturity in 0.10 - 0.12 ppm ozone concentrations showed reductions or delays in bract or flower development, as well as depressed growth. Average leaf area was reduced by 10 percent in geranium and bract area decreased by 39 percent in poinsettia grown in air containing 0.12 ppm ozone. This exposure constituted a higher average dose than would be experienced under ambient conditions due to ambient diurnal fluctuations. Carnation showed significant delay in flower bud initiation in 0.10 ppm ozone, but otherwise, bud development was not affected.

4. Nitrogen Oxides

Investigations of the effects of nitrogen oxides on vegetation have suffered from several handicaps, including the numerous atmospheric reactions of the several oxides, the rapid fluctuations of their ambient levels, the lack of an acceptable measurement techniques, and the synergistic. effects with sulfur dioxide and oxidants. Most studies have attempted to circumvent these problems by adopting nitrogen dioxide (NO_2) as a proxy for all nitrogen oxides and by relying on controlled laboratory exposures or on concentration predictions based on emission levels. Principal studies have examined the effects on pinto bean, tobacco, and tomato (Taylor and Eaton, 1966), navel orange (Thompson et al., 1971), and pine trees (Stone and Skelly, 1974).

Effects of nitrogen dioxide exposures on pinto bean, tobacco and tomato were investigated by Taylor and Eaton (1966) in temperature-controlled fumigation chambers. Several cultivars of tobacco exhibited leaf damage after nine-hour exposures to 4.72 mg/m^3 NO_2 levels, but there was no damage after five-hour exposures. Results of longer exposures at lower concentrations, closer to ambient levels of pinto bean and tomato, are shown in Tables 13 and 14. Significant differences in weight and chlorophyll content were observed for exposures over 10 days to levels between 0.61 - 1.03 mg/m^3.

Table 13. Effect of NO_2 Exposure on Growth Rate of Pinto Bean Seedlings and Chlorophyll Content of Primary Leaves

Days exposed	Conc. NO_2 (mg/m^3)	Fresh weight (g)		Dry weight (g)		Chlorophyll content (mg/g) Fresh weight (g)		Chlorophyll content (mg/g) Dry weight (g)	
		NO_2	Check	NO_2	Check	NO_2	Check	NO_2	Check
10	0.62	1.41	1.94*	0.110	0.141*	2.26	1.84*	25.4	22.9*
19	0.62	3.85	4.53*	0.382	0.423*	2.25	1.90*	24.95	21.58**
11	0.62	1.76	2.06*	0.195	0.208**	3.01	2.40*	27.12	23.52*

* Significant difference at 1% level.
** No significant difference.

Statistical analysis by t test; N = 20

Source: Taylor and Eaton, 1966

Table 14. Effect of NO_2 Exposure on Growth of Pearson Improved Tomato Plants

Days exposed	Conc. NO_2 (mg/m^3)	Fresh weight (g)		Dry weight (g)	
		NO_2	Check	NO_2	Check
10	0.31-0.43	14.3	18.0*	0.10	0.15*
14	0.53-1.17	2.3	2.8**	0.17	0.18***
19	0.82-1.03	8.7	10.6*	0.66	1.04**
22	0.27-0.53	6.22	7.94**	0.47	0.59**

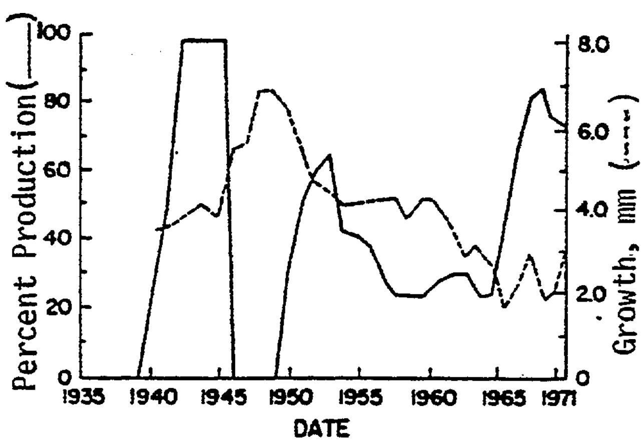
* Significant difference at 5% level.
** Significant difference at 1% level.
*** No significant difference.

Statistical analysis by t test; N = 20

Source: Taylor and Eaton, 1966

Thompson et al. (1971) exposed navel orange trees to NO_2 concentrations up to twice ambient levels. Leaf drop was compared with that of control trees exposed to carbon-filtered air. The slightly higher leaf drop from trees exposed to NO_2 was determined to be statistically insignificant. Although the data cannot be used to develop a damage function, they do suggest the presence of a threshold.

An ingenious, but not very successful attempt to determine the relationship between NO_2 emission levels and amount of growth in 43 white pine trees near Radford, Virginia was made by Stone and Skelly (1974). The NO_2 levels were estimated on the basis of production volume in the nearby Radford Army Ammunition Plant, a major local source of nitrogen oxides. Growth rates were determined by measuring the width of the annual growth ring, The inverse correlation shown in Figure 15 is not very convincing and suggests either a poor relationship between production and NO_2 levels, or the presence of other growth-stunting factors or, most likely, both.



Source: Stone and Skelly, 1974

Figure 15. Relationship Between NO_2 Emissions Represented by Ammunition Plant Production and Growth Rate of White Pine Trees

5. Acid Rain

Acid rain is formed when rain drops scavenge sulfuric, nitric and hydrochloric acids from airborne aerosols and its severity is measured by its pH. Acid rain has been recently brought to light as a serious environmental problem in Europe (RMFA, 1972) and in the eastern U.S. (Likens and Borman, 1974). Measurements of pH between 3.0 and 4.0 have been rather frequent, and values as low as 2.0 have been reached.

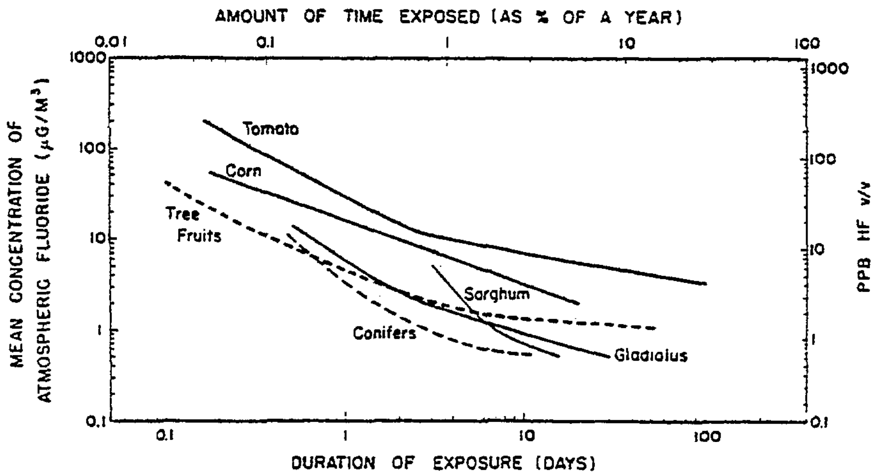
Studies in Hawaii reported that certain tomato plants grown under rain shelters averaged 5 kg per plant of saleable fruit, whereas plants grown in the natural rainfall yielded no saleable fruit due to blossom drop, poor fruit set, or reductions in fruit quality (Kratky <u>et al.,</u> 1974). A pH drop from 5.0 to 4.5 in the rainwater caused a reduction in pollen tube germination (a necessary prerequisite for fruit growth) from 5.3 to 2.2 percent.

Yellow birch seedlings exposed to acid mist under greenhouse conditions showed marked decreases in estimated weight when pH dropped below 3.0 and significant mortality rate at pH 2.3 (Wood and Borman, 1974). The acid mist treatments were applied for one six-hour period each week over a period of 120 days to simulate natural conditions.

6. Fluorides

Fluorides are emitted during production of aluminum, steel, ceramics, and phosphate fertilizers, and thus, present a localized pollution problem. Gaseous hydrogen fluoride is taken up and accumulated by the plant's leaves, though particulate fluorides also play a role. Fluoride injury is thought to take place through direct interaction with plant enzymes or tissues, or through induced changes in cellular nutrient and hormone balance (McCune and Weinstein, 1971).

Threshold levels of foliar injury and yield reduction have been charted for conifers, corn, gladiolas, sorghum, tomato, and tree fruits by McCune (1969). His results show that even between such diverse plant types as tomato and conifers, threshold levels for any particular length of exposure fall within a factor of ten and they are much closer for other plants (see Figure 16). More detailed information on the individual species has been reported by the National Academy of Sciences (NAS, 1971). Relations between fumigation levels and total fluoride content has been derived for alfalfa and a number of other forage crops. Although these threshold values are important, the establishment of useful damage functions will require quantification of yield reduction as a function of varying concentrations over the growing season.



Source: McCune, 1969

Figure 16. Threshold Levels of Foliar Injury and Yield Reduction for Several Plants.

Other studies have shown that fluoride uptake and effects are influenced by moisture, temperature, and sunlight (Poovaiah and Weibe, 1973). Soybeans exposed to 15 ml/l fluoride levels for four days exhibited 60-70 percent reductions in transpiration rate, whereas exposures of six hours per day produced lesser reductions. These effects correlated qualitatively with the extent of observed foliar injury. Drought conditions before exposure were found to reduce subsequent fluoride injury due to decrease stomatal uptake, while post-fumigation drought increased injury (Poovaiah and Weibe, 1973). Conditions of high temperature or sunlight were also found to accelerate foliar injury by as much as 40 percent.

C. DAMAGE TO MATERIALS

Investigations of the effects of air pollutants on materials are less complicated than those of health or vegetation effects, because of the opportunity to control both exposure and the target population. Nevertheless, useful dose-effect functions in this area are not many. This section examines the effects of sulfur dioxide, particulates, and nitrogen dioxide and ozone, following some introductory general remarks.

1. General Remarks

Investigation of the effects of air pollutants on materials permits the control of both exposure and the makeup of the target population. Nevertheless, useful dose-effect functions in this area are largely confined to representations of the corrosion of metals by sulfur oxides and the soiling of exposed surfaces by particulates. Other pollutants studied include particulates, nitrogen oxides, and oxidants. Target populations are paper, textiles, leather, paints and dyes, rubber, plastics, metals, ceramics, and stone (see Table 15).

Effects of long-term exposures have been determined by exposing test panels to ambient conditions for long periods of time. The results of these field studies have been flawed by poor ambient level measurements and failure to account for other pertinent environmental variables. Laboratory studies have attempted to determine short-term effects by subjecting test panels to elevated pollutant concentrations. Recent laboratory experiments have employed more realistic concentrations. Humidity exerts a major influence on the severity of most effects, with temperature and air flow playing lesser roles.

Since most materials of interest are available in a great variety of compositions and physical and chemical characteristics, it is not surprising that effects of a given pollutant under a specified set of conditions may vary widely from one material to another. For this reason, the target population must be specified accurately, as was the case with health and vegetation effects. On the other hand, the close similarity between different samples of the same material affords a high degree of precision and the determination of standard errors on

Table 75. Selected Studies of Material Effects of Major Air Pollutants

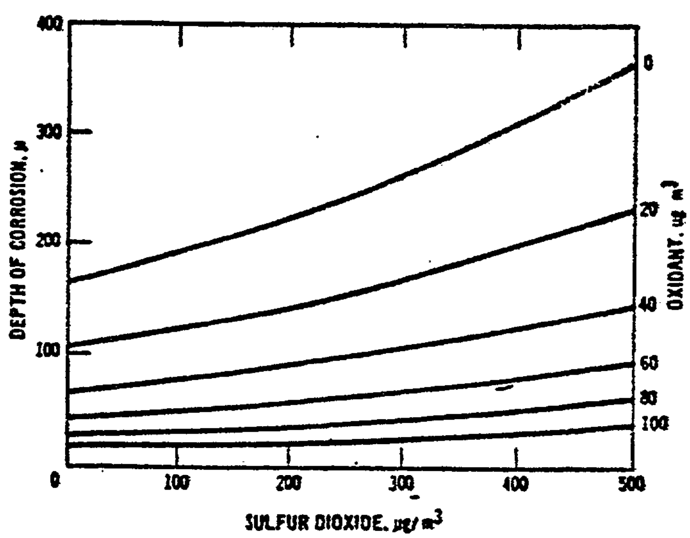
Pollutant	Material	Effect	Reference
SO_2	Steel	Corrosion	Sereda, 1960
SO_2	Steel	Corrosion	Haynie and Upham, 1971
SO_2	Zinc	Corrosion	Guttman, 1968
SO_2	Zinc	Corrosion	Dunbar, 1968
SO_2	Zinc	Corrosion	Haynie and Upham, 1970
SO_2	Aluminum	Corrosion	Azis and Godard, 1959
SO_2	Copper	Corrosion	Mattsson and Holm, 1968
SO_2	Nickel and titanium alloys	Corrosion	Van Rooyen and Copson, 1968
SO_2	Nickel and titanium alloys	Corrosion	Greenlee and Plock, 1968
SO_2	Cotton fabric	Reduction in tensile strength	Brysson et al., 1967
SO_2	Limestone and marble	Decay	Gauri and Sarmma, 1973
SO_2, NO_2, O_3	Aluminum	Corrosion-induced cracking	Haynie, 1975
SO_2, NO_2, O_3	Paints	Erosion	Spence et al., 1974
SO_2, NO_2, O_3	Cellulosic fabric	Dye fading	Upham et al., 1974
O_3	Paints	Erosion	Spence et al., 1974
Particulates	Paints	Increased maintenance	Michelson and Tourin, 1967
Particulates	Paints	No significant maintenance change	Booz, Allen and Hamilton, 1970
Particulates	Paints and exposed	Decrease in reflectance	Beloin and Haynie, 1973
Particulates	Electrical contacts	Tarnishing	Campbell, 1972
Particulates	High-voltage insulators	Flashover and current leakage	Robinson, 1972
Particulates	Electronic components	Failure	Baker, 1975

the basis of replicate experiments- Results are typically expressed in terms of percentage loss of useful life or increased frequency of maintenance and replacement.

2. Sulfur Oxides

Sulfur oxides in the presence of moisture and oxidants, probably in the form of sulfuric acid, has been found responsible for the corrosion of metals, damage to electrical contacts, deterioration of paper, textiles, leather, finishes and coatings, and erosion of building stone through conversion of calcium carbonate to the soluble sulfate. Investigations of metals have focused on steel (Sereda, 1960; Haynie and Upham, 1971), zinc (Dunbar, 1968; Guttman, 1968; Haynie and Upham, 1970), aluminum (Azis and Godard, 1959; Haynie, 1975), copper (Mattsson and Holm, 1968), nickel (Van Rooyen and Copson, 1968), and titanium (Greenlee and Plock, 1968).

Haynie and Upham (1971) exposed three types of steel at eight urban sites to determine correlations between sulfur dioxide and nitrogen oxide and oxidant levels with corrosion of the metal. They found that corrosion increased with higher sulfur dioxide levels, but decreased with rising oxidant concentrations, which apparently acted antagonistically toward sulfur dioxide. The results of the investigation are presented in Figure 17 as a family of curves representing different oxidant levels and a plot of depth of corrosion vs. sulfur dioxide concentration over a ten-year period.



Source: Haynie and Upham, 1971

Figure 17. Relationship Between SO_2 and Oxidant Concentrations and Depth of Corrosion of Carbon Steel.

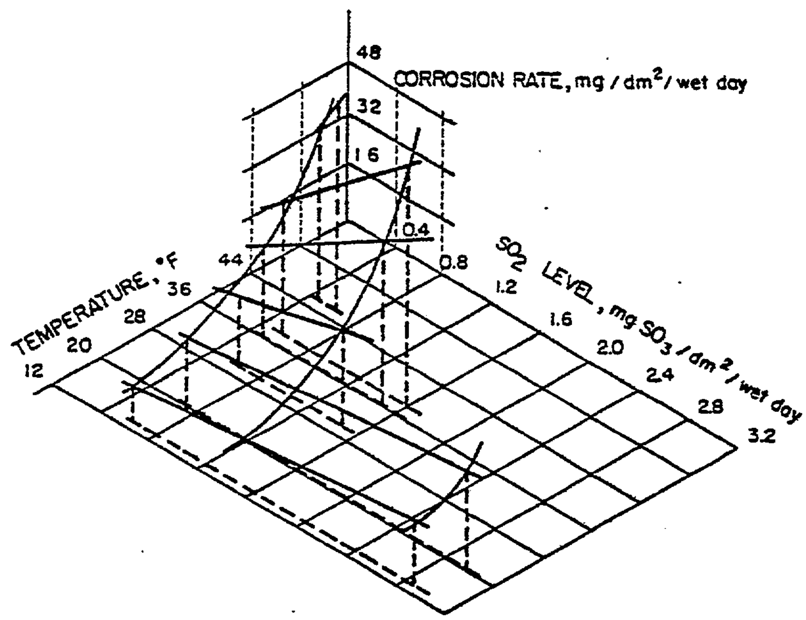
Sereda (1960) found significant synergistic effects of SO_2 and temperature on corrosion of steel. The results are plotted in Figure, 18 as a three-dimensional surface representing corrosion rate as a function of both SO_2 concentration and temperature. The surface was then approximated by a plane and its equation was formulated to least squares fit as follows:

$$Y = 0.131x + 0.018z + 0.787,$$

where Y = log corrosion rate, in mg/dm^2/wet day

X = SO_2 pollution rate, in mg SO_3/dm^2/day

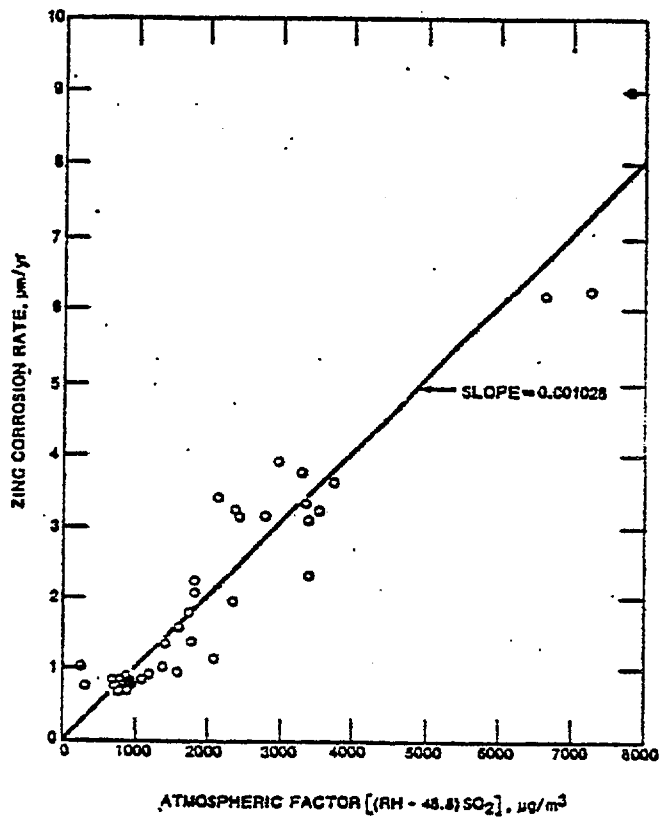
Z = average monthly temperature during wet days, in °F.



Source: Sereda, 1960

Figure 18. Three-Dimensional Relationship Between SO_2 level, Temperature and Corrosion Rate of Steel.

The importance of zinc is related to that of steel because zinc is used in the galvanization process to protect steel. An initial investigation by Guttman (1968) disclosed that SO_2, relative humidity, and to some extent, temperature affects corrosion in raw zinc. Another study by Dunbar (1968) found no significant difference in weight loss among three grades of zinc ranging in purity from 99 - 99.9% upon exposure to SO_2 and moisture. In the experiment cited earlier for steel, Haynie and Upham (1970) exposed test samples in eight urban areas and found a linear relationship between corrosion rate and an atmospheric factor composed of SO_2 concentration and relative humidity (see Figure 19). This study is described in greater detail in Section IV D.

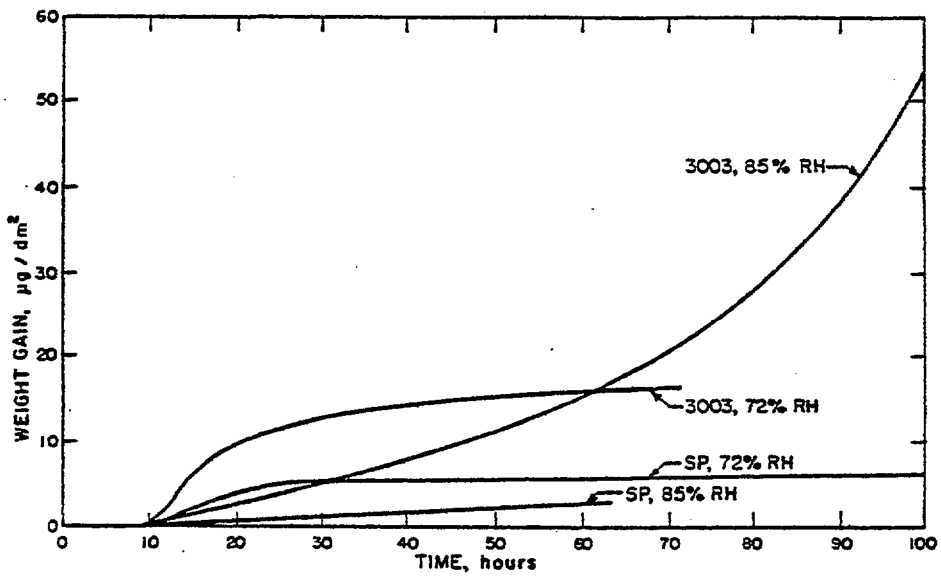


Source: Haynie and Upham, 1970

Figure 19. Relationship Between SO_2 Concentration, Relative Humidity, and Corrosion Rate of Zinc.

Azis and Godard (1959) investigated the corrosion of aluminum under laboratory conditions at SO_2 levels of 280 ppm. The results are displayed in Figure 20 as a family of curves representing several alloys and different levels of relative humidity on a plot of weight gain due to corrosion vs. time. Unfortunately, the study fails to relate corrosion rate with varying SO_2 concentrations.

The effects of SO_2, NO_2, and ozone on corrosion-induced cracking in aluminum were investigated by Haynie (1975). The bending strength of the metal was found to decrease with increasing concentration of SO_2. The particular alloy under study had been stressed for over 2,000 hours at the relative humidity of 80% and a temperature of 29°C.



Source: Azis and Godard, 1959

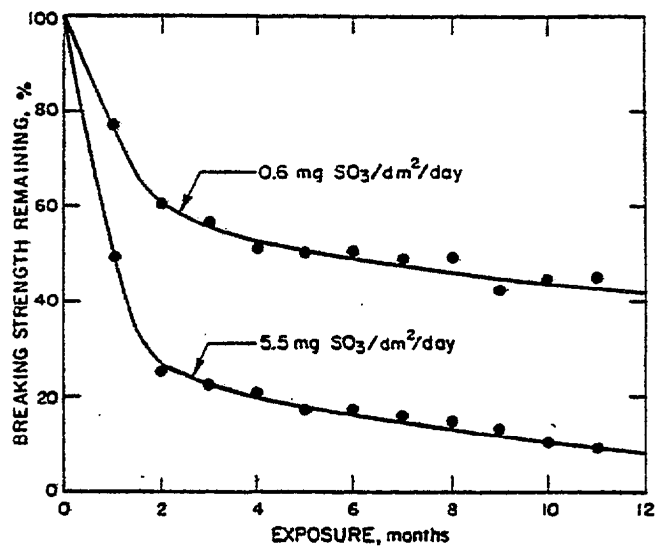
Figure 20. Relationship Between SO_2 Exposure Time and Corrosion Rate of Two Aluminum Alloys at 72 and 85 Percent Relative Humidity and 280 ppm SO_2 concentration.

Copper and its alloys have been investigated in a less quantitative fashion. A study by Mattsson and Holm (1968) reported corrosion rates of 0.2-0.6 µm/year at SO_2 concentrations of 8 $\mu g/m^3$ and of 0.9-2.2 µm/year at SO_2 levels of 70 $\mu g/m^3$.

Studies of nickel and titanium alloys by Van Rooyen (1968) and by Greenlee and Plock (1968) found most of these metals highly resistant to air pollutants, even in heavily industrial atmospheres.

The more significant studies of the effects of SO_2 exposure on other materials were performed on cotton fabrics (Brysson et al., 1967), carbonate stone (Gauri and Sarma, 1973), and four types of paints (Spence et al., 1974).

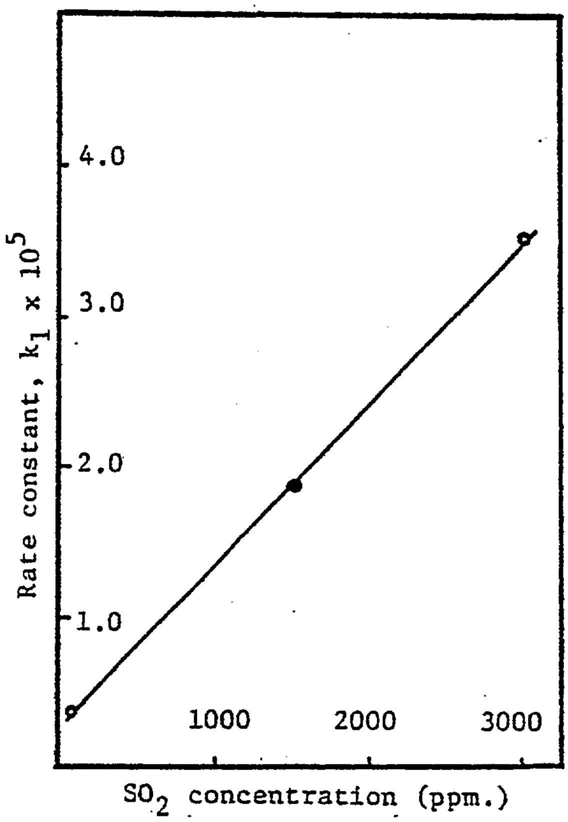
Brysson exposed cotton fabrics to sulfates at seven locations in the St. Louis area and found significant reduction in their service life. The results are plotted in Figure 21 in the form of tensile strength vs. time of exposure at two levels of SO_3.



Source: Brysson et al., 1967

Figure 21. Relationship Between SO_2 Exposure Time and the Tensile Strength of Cotton Fabric at Two Levels of SO_3.

Effects of SO_2 exposure in the presence of moisture on carbonate stone, including limestone and marble, have been measured in terms of the reaction rate between SO_2 and calcite by Gauri and Sarma (1973). The variation in reaction rate constant with SO_2 concentration for one type of marble is shown in Figure 22.



Source: Gauri and Sarma, 1973

Figure 22. Relationship Between SO_2 Concentration and the Reaction Rate for Alabama White Marble.

Spence et al. (1974) exposed four types of paints to SO_2, NO_2, and ozone and found SO_2 to be the primary damaging agent. Experiments were monitored in exposure chambers under controlled pollutant concentrations, temperature, and relative humidity. The combined effects of SO_2 concentration and relative humidity accounted for over 60 percent of the variability in erosion rates.

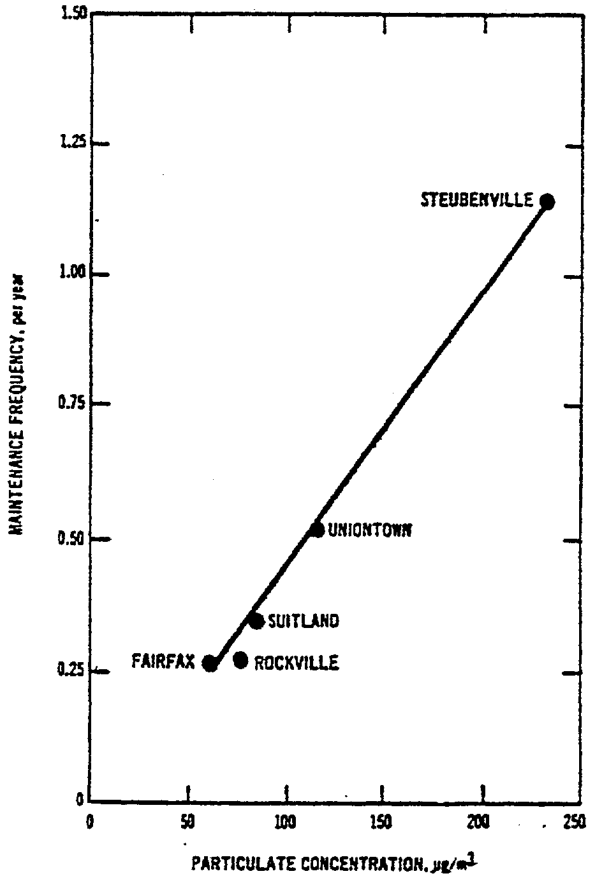
3. Particulates

The major effects of particulate exposure on materials are the soiling and deterioration of painted and other exposed surfaces, and a number of investigations have addressed this topic (Michelson and Tourin, 1967; Booz, Allen and Hamilton, Inc., 1970; Beloin and Haynie, 1973). Degradation of painted surfaces may take the form of chalking, cracking, erosion, flaking, or changes in the color or tensile strength of paint films. Particulates have also been held responsible for affecting the operation of electrical contacts and for causing electric flashover from insulators on high tension wires (Campbell, 1972; Robinson, 1972; Baker, 1975).

The frequency of maintenance of painted surfaces exposed to particulates has been investigated in Philadelphia (Boot, Allen and Hamilton, Inc., 1970) and in five other towns and suburbs (Michelson and Tourin, 1967). The results of the two studies are in sharp disagreement, because responses in the five cities record substantial increase in maintenance frequency with particulate concentration (see Figure 23), whereas the Philadelphia study found no significant differences (Table 16). One reason for the discrepancy may be the covariation of income and attitude towards maintenance with air pollution levels in the Philadelphia study.

The relationship between particulate concentration and rate of soiling for painted surfaces as well as cedar siding, asphalt shingles, concrete blocks, limestone, brick, and window glass was investigated by Beloin and Haynie (1973) at five test sites in Birmingham, Alabama. The materials were exposed to ambient suspended particulates at levels between 60-260 $\mu g/m^3$ over a two-year period. Soiling was expressed in terms of reflectance measurements for opaque surfaces and in terns of haze measurements for glass. The degree of soiling of painted cedar siding was found to be proportional to the square root of the particulate exposure (see Figure 24), whereas the degree of soiling for shingle siding was directly proportional to the exposure. However, the soiling of limestone, concrete, brick, and glass surfaces exhibited no clear correlation with particulate exposure.

Particulates have been found to affect the operations of electrical contacts, components, and insulators by forming a surface film (Campbell, 1972). The rate of formation on brass contacts depends strongly on both particulate concentration and relative humidity, whereas silver contacts are not significantly affected. Most of these investigations have not produced quantitative relationships that are worthy of reporting here (Robinson, 1972; Baker, 1975).



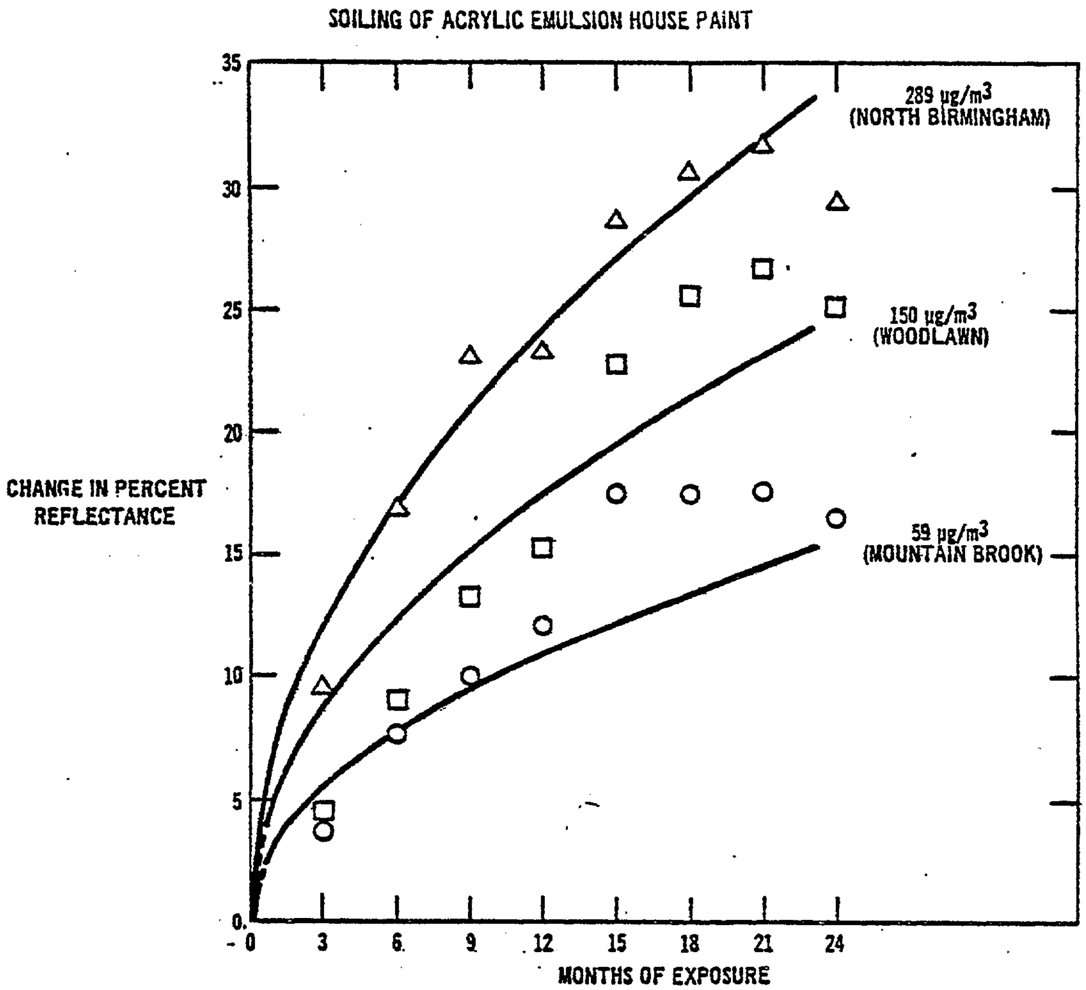
Source: Michelson and Tourin, 1967

Figure 23. Relationship Between Exterior Repainting Frequency and Particulate Concentration.

Table 16. Mean Annual Frequency of Exterior Wall Painting as a Function of Particulate Concentration in the Philadelphia Area.

Particulate concentration ranges, µg/m³	Exterior wall painting	
	Mean annual frequency	Standard error of mean
<75	0.28	0.016
75 to 100	0.35	0.053
100 to 125	0.35	0.041
> 125	0.29	0.055

Source: Booz Allen and Hamilton, Inc., 1970



Source: Beloin and Haynie, 1973

Figure 24. Relationship Between Particulate Concentration, Exposure Time, and Soiling of House Paint.

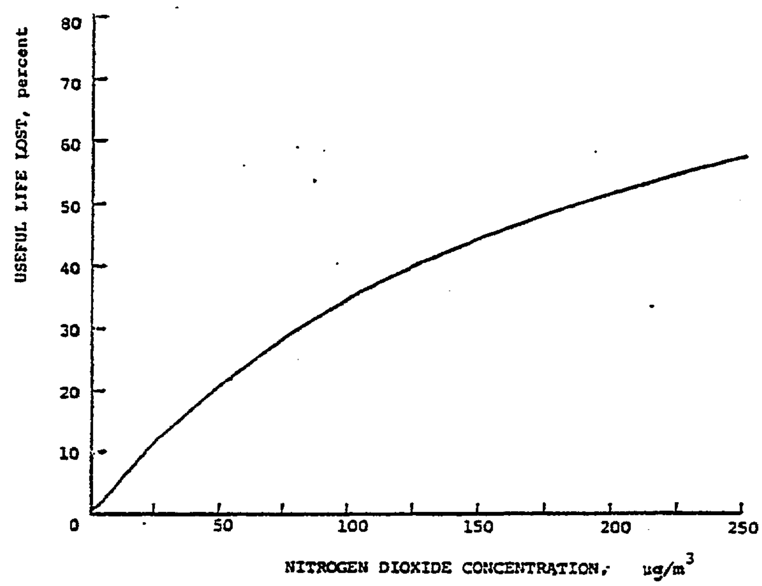
4. Oxidants and Nitrogen Oxides

Ozone damage to materials has taken the form of premature fading of fabric dyes (Salvin, 1972), and increased erosion rate of paint (Spence, et al., 1974). Ozone has also been found to act antagonistically toward sulfur dioxide in the corrosion of steel, thus decreasing the corrosion rate (see Figure 17). Nitrogen dioxide has to date been linked mainly with dye fading in fabrics (Salvin, 1972). However, a quantitative relationship was not established.

In the previously mentioned study of paints in a controlled chamber, Spence et al. (1974) found that acrylic coil coating was significantly affected only by ozone. Upon exposure to low levels of SO_2 and NO_2 and high relative humidity, the erosion rate increased from 0.735 μm/yr. at 157 μg/m^3 O_3 level to 1.150 μm/yr. at the 980 μg/m^3 level. This increase is, however, only slightly larger than the standard error.

In another test chamber study, red and blue cellulosic fabrics were exposed to SO_2, O_3, and NO_2 to assess color fading (Upham et al., 1974). NO_2 was found to contribute to fading and loss of useful fabric life both directly and in synergism with relative humidity. At 60 percent relative humidity and 25°C, the simplified dose-effect relationship is plotted in Figure 25 and expressed by the equation:

$$\text{Percentage of Useful Life Lost} = \frac{0.525\ NO_2}{1 + 0.00525\ NO_2}$$



Source: Upham et al., 1974

Figure 25. Relationship Between NO_2 Concentration and Fading of Plum Fabric.

D. OTHER EFFECTS OF AIR POLLUTION

Air pollutants affect a number of other target areas beyond human health, vegetation, and materials. The more important among these are aesthetic and meteorological effects. Quantitative relationships for these areas are very scarce because of lack of sufficient interest and/or the difficulties of measuring the effects.

1. Aesthetic Effects

Aesthetic effects may take the form of reduced visibility or odors. All of the major pollutants, with the possible exception of carbon monoxide, can contribute to the first problem and a host of minor pollutants, including ammonia, hydrogen sulfide, and mercaptans, are responsible for the second. The relationships between pollutant levels and visibility are relatively straightforward. Charlson (1969) derived a rather simple equation relating visibility to aerosol levels, which yielded a correlation coefficient of 0.82 for 238 readings in a variety of locations. Odor measurement as a function of pollutant concentration is a much more formidable problem, because the effect is largely psychic, and thus, difficult to measure.

Aesthetic effects have been usually measured in monetary terms by assessing the people's willingness to pay for pollutant abatement leading to a reduction of the offensive condition. This may be accomplished through public opinion surveys, or through studies of changes in property values as a function of air pollution levels. For example, Mason (1972) and Vars and Sorenson (1972) surveyed the opinion of tourists on heavy smoke problems in the Willamette Valley in Oregon caused by the burning of grasses. Randall *et al.* (1974) carried out a series of so-called bidding games designed to assess willingness to pay for abatement of particulate emissions among several population subgroups in the Four Corners area in the Southwest.

2. Meteorological Effects

Air pollution has been held accountable for changes in precipitation patterns and in the mean temperature of the earth's atmosphere. Air pollutants also contribute to contamination of water and soil through deposition by gravity or by precipitation.

Air pollutants have been found to cause either increases or decreases in precipitation, depending on local meteorological and topographic conditions (Hersey, 1970). Unfortunately, the data base is too small for a suitable dose-effect function.

Mitchell has traced the relationship between atmospheric dust level, contributed principally by volcanic eruptions, and the drop in the mean temperature of the earth's atmosphere. This has potentially great importance, because a 1.6 percent decrease in the amount of solar radiation reaching the earth has been estimated to be capable of producing severe glaciation (Davis, 1971). However, Mitchell's results are inconclusive, because the relationship exhibits varying magnitudes and time lags.

Investigations of the contribution of air pollutants to the contamination of surface waters and soil have been conducted on Lake St. Claire (Whelpdale, 1974), on Lake Michigan (Skibin, 1973), in the Sierra Mountains (Yoshimitsu and Patterson, 1974), and in England (Hallsworth and Adams, 1973). Here again, the results are not sufficiently consistent and well-defined to permit the development of dose-effect functions.

E. EFFECTS OF WATER POLLUTION

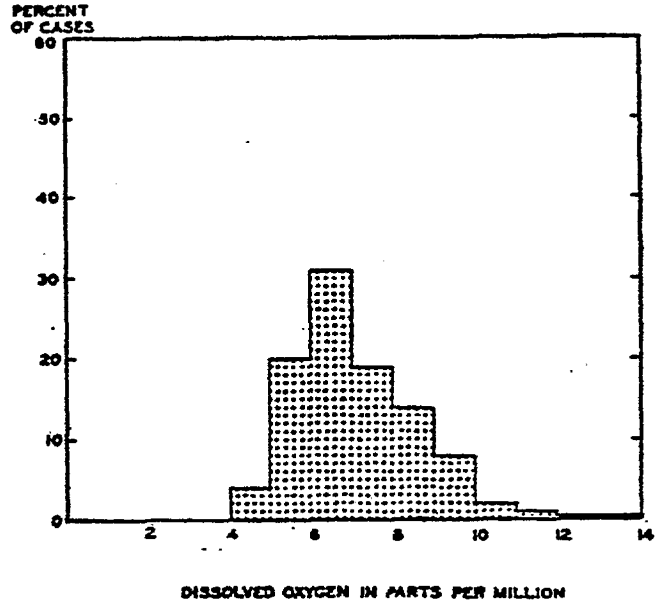
Effects of water pollution have received relatively less quantitative scrutiny than effects of air pollution, perhaps because the largest effect, loss of recreation, is so difficult to measure, and because most effects are attributable to different combinations and concentrations of various pollutants. Nevertheless, dose-effect functions have been developed for the effects of various pollutants on fish and other aquatic organisms, as well as on household plumbing fixtures,

1. Effects on Fish

Dose-effect functions involving fish and other aquatic organisms have been developed for dissolved oxygen and industrial chemicals (Ellis, 1937), acidity (Lackey, 1939), dissolved solids (Baldwin and Saalfield, 1962; Beeton, 1965), suspended solids (Dow Chemical Company, 1968), and Kraft mill effluent (Stoevener et al., 1972).

The quantitative relationship between dissolved oxygen (DO) concentration and a desirable mix of fish species has been investigated by Ellis (1937), who found the optimum level to be between 6 and 7 ppm (see Figure 26). A desirable mix was defined as including trout, bass, sunfish, perch, suckers, buffalo, and catfish in good condition at the time of sampling. Ellis also investigated survival rates of goldfish in varying concentrations of several types of industrial waste. The results for sulphur and selenium compounds are shown in Table 17.

Ellis's findings of an optimum DO level for aquatic organisms were confirmed by Lackey (1939) who investigated the relationship between dissolved oxygen and the diversity of benthic organisms in the Shenandoah River (see Table 18). These organisms form an important element of the fish food chain and these results could be responsible for Ellis's findings. Lackey also found that the number of plankton species increased from 10 to 23 when the pH range was raised from 1.8-3.9 to 4.8-7.2.



Source: Ellis, 1937

Figure 26. Relationship Between DO Level and Percent of Cases with Desirable Fish Mix.

Table 17. Survival of Goldfish in Solutions of Sulphur and Selenium Compounds

Substance	Parts per million	pH	Survival Time
Ammonium sulfide	1,000	7.9	15 - 90 minutes
	100	7.8	72 hours - > 4 days
	10	7.7	> 4 days
	1	7.7	> 4 days
Hydrogen sulfide	1,000	6.5	45 - 60 minutes
	100	7.3	3 - 4 hours
	10	7.6	> 96 hours
	1	7.7	> 4 days
Sodium Sulfite	1,000	7.6	3 - 72 hours
	100	7.6	> 96 hours
	10	7.6	> 4 days
	1	7.8	> 4 days
Sodium selenite	1,000	7.4	60 - 130 minutes
	100	7.7	8 - 19.5 hours
	10	7.3	98 - 144 hours

Source: Based on Ellis, 1937

Table 18. Relationship Between Dissolved Oxygen Level and the Number and Weight of Benthic Organisms

DO (ppm)	No. of Benthic Organisms	Weight of Benthic Organisms
6.0	912	6.5
3.9	108	0.4
8.4	528	4.1

Source: Lackey, 1939

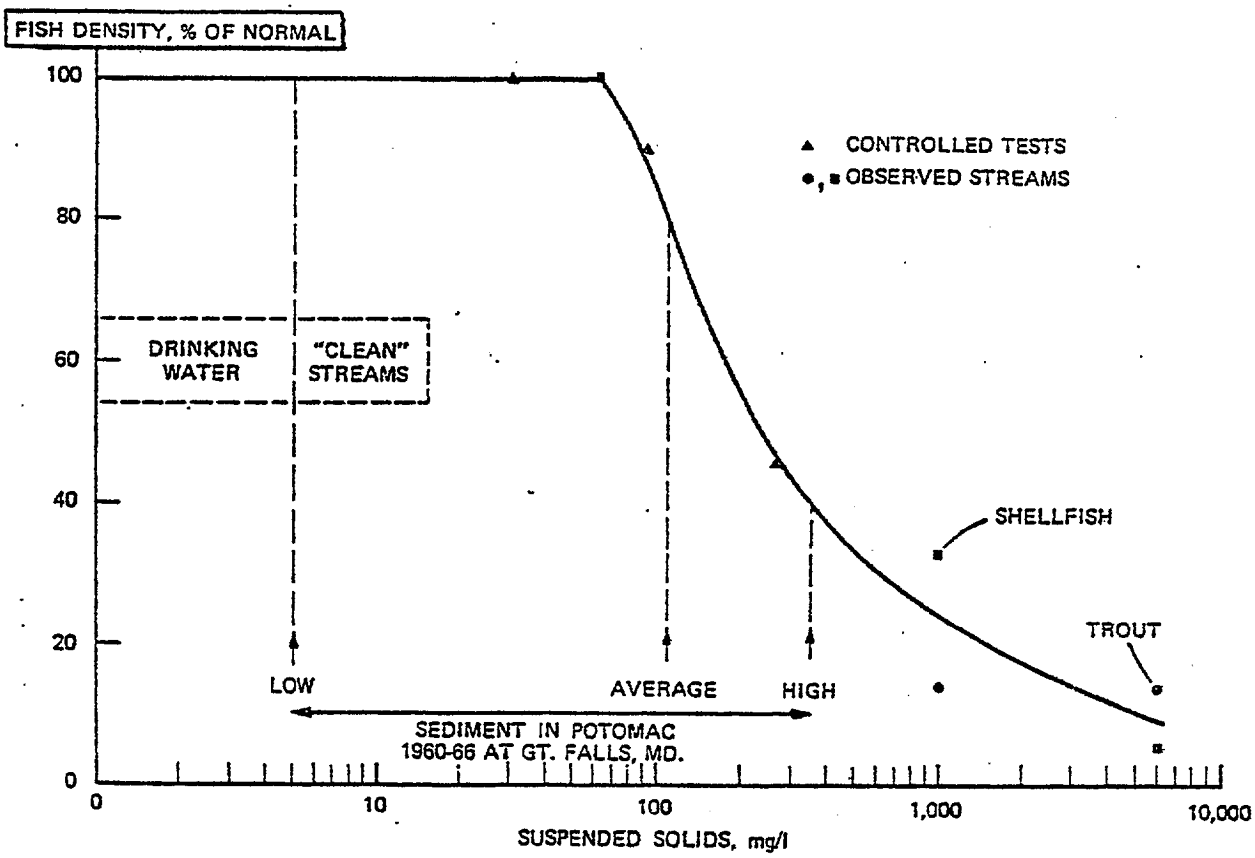
Several investigators have attempted to correlate concentrations of dissolved solids with fish productivity in the Great Lakes on the basis of records dating back to the beginning of this century (Baldwin and Saalfield, 1962; Beeton, 1965). The fish were lake herring, blue pike, and yellow perch, whereas the dissolved solids included sodium, potassium, calcium, chloride, and sulfate. Although some negative correlation can be noted in the overall trend, the relationship is not at all consistent..

On the other hand, fish density in the Potomac River has been found to be strongly dependent on the concentration of suspended solids (Dow Chemical Company, 1968). The results are displayed in Figure 27, which shows that fish density falls to ten percent of the normal volume at a concentration of 6000mg/l. Trout and shellfish were the primary species affected.

In a related study in the Potomac River, the Great Lakes, and Yaquina Bay, fish densities have been related to concentrations of both suspended solids and Kraft mill effluents (Stoevener et al., 1972). Specifically, the effects of exposure to Kraft mill effluent on flounder in Yaquina Bay are shown in Figure 28.

2. Other Effects

Other effects of water pollutants may take the form of loss of recreation and aesthetic enjoyment, damage to health and materials, and the additional expense of treating municipal, industrial, and agricultural

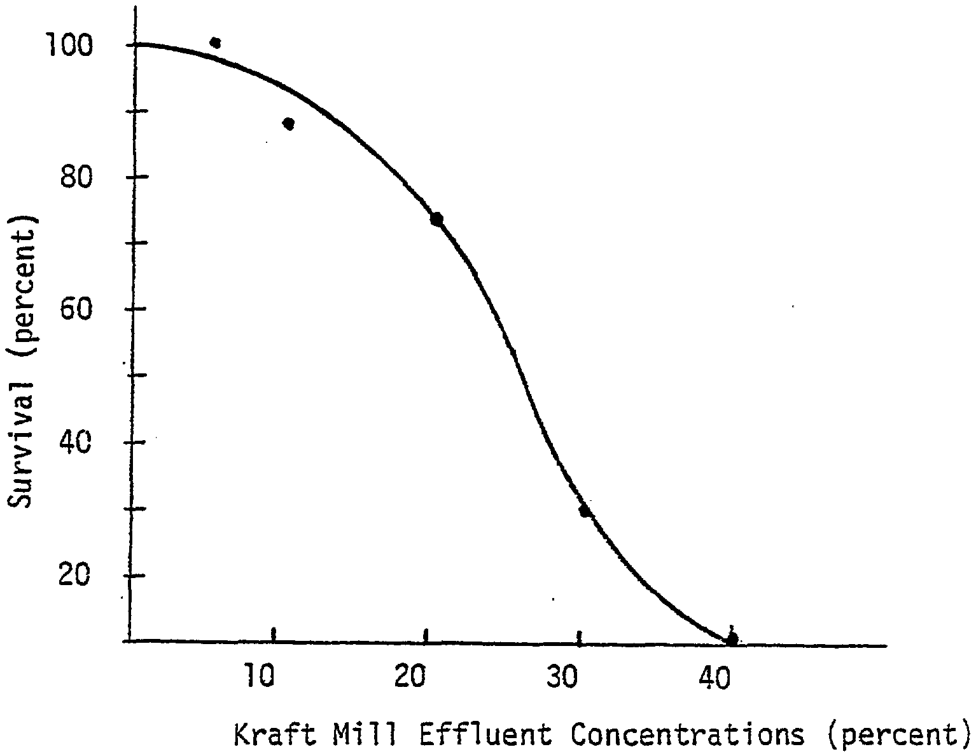


Source: Dow Chemical Co., 1968

Figure 27. Relationship Between Suspended Solids and Trout and Shellfish Density.

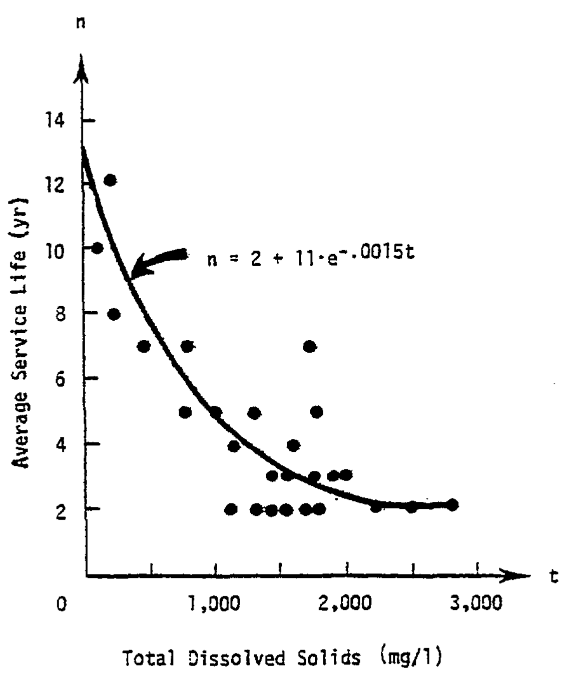
water supplies. Few of these relationships have been investigated sufficiently to permit the development of a dose-effect function, partly because the pollutants act in varying combinations and concentrations and partly because the effects are difficult to measure.

One such function was formulated by Tihansky (1974) linking total dissolved solids concentration with the life expectancy of household plumbing fixtures. The results for toilets are displayed in Figure 29.



Source: Based on Stoevener, 1972

Figure 28. Survival of Starry Flounder After 48 Hours in Various Concentrations of KME.



Source: Tihansky, 1974

Figure 29. Relationship Between Dissolved Solids and Life Expectancy of Toilets.

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III. ANALYTICAL METHODOLOGY

In spite of the potential importance of dose-effect functions and the amount of effort that has gone into generating the necessary data, the methodology for developing these functions and handling of the attendant problems and uncertainties are still in their infancy. This chapter presents the first comprehensive and systematic exposition of this subject by tracing the methodology through the progressive stages of study design, measurement of ambient levels, determination of exposure, determination of effect, estimation of functional relationships, and presentation of results.

A. DESIGN OF STUDY

Design of the study is a crucial stage in the dose-effect development process, for it sets the pattern for much of the subsequent effort and determines the usefulness of the results. The major decisions involve selection of study parameters and type of study (epidemiological or field, clinical, and toxicological or laboratory).

1. Selection of Study Parameters

The principal parameters to be selected in the design of a dose-effect study are:

- Pollutants and measures
- Effects and measures
- Population at risk
- Time frame and geographic coverage

The selection of these parameters is generally dictated by the intended use of the study, availability of data, and amount of funding, but specific parameters are subject to additional considerations. For example, the important considerations in selecting a pollutant for study may be listed as follows:

- Synergistic or antagonistic interactions
- Meteorological conditions
- Type and unit of measure
- Observation interval

Consideration of potential synergistic and antagonistic interactions of the pollutant under study with other species that may be present and the impact of certain meteorological conditions are likely to determine the type and amount of data to be collected. Decision on type of measure (e.g., mean, median, peaks, excesses), units (e.g., micrograms per cubic meter of air, parts per million), and observation intervals (e.g., hourly, daily, monthly, annual) is governed both by availability of data and by the desired precision and level of aggregation of the results.

Characterization of the population at risk, i.e., the human, vegetative, or material population exposed to pollutants under study, helps to determine its potential susceptibility to various levels of air pollution. Consequently, it is useful in defining more precisely the effects associated with a given exposure. Characterization of population at risk can also provide useful indications for allocation of resources and setting of priorities in air pollution abatement. For example, a higher clean-up priority could be assigned to an area containing a large population of older people or those exposed to high occupational pollution than to another area with a smaller population of relatively healthy people, not otherwise exposed to harmful pollutants. Such decision process can be refined further through control of specific pollutants.

Human susceptibility and resultant response to toxicological and physical stress produced by air pollutants is defined in accordance with certain intrinsic traits, such as age, race, sex, and general health, as well as by such extrinsic characteristics, as employment, income, educational level, and general environmental conditions. The age subpopulations that are considered particularly susceptible to observable effects are the very young (under 20) and the old (over 65). Genetic makeup, most readily defined along racial lines, is another predeterminant of susceptibility. Sex, a third determinant, is seldom considered, because it is distributed fairly evenly in most community studies.

The type or place of employment is an important indicator of exposure to industrial air pollution, and the subpopulation engaged in manufacturing should be identified as a minimum. Educational level relates to an awareness of the need for proper nutrition, health care, and protection from air pollutants. Finally, family income again correlates with the nutritional and health care levels, but may also serve as an indicator of the willingness to pay for abatement of air pollution in economic studies. Although these intrinsic and extrinsic traits and characteristics are not considered etiological agents of disease, studies of their correlation with health effects have been helpful in isolating the likely agents, such as specific air pollutants, and in shaping social policy. (Takacs and Shea, 1975).

2. Epidemiological Field, and Clinical Studies

Epidemiological studies are by far the most common approach to the assessment of health effects of air pollutants. These studies involve collection of available air quality and health effects data and measurement of their relationship and degree of correlation. Clinical observations of individuals who come under medical or clinical attention represent a rather limited source of health effect information. Field observations apply to assessment of air pollution effects on vegetation and materials. In most other respects, these two approaches are rather similar to epidemiological studies.

In the performance of epidemiological studies, the investigator can select to a large extent, but not control, composition of the air, extent of exposure, population at risk, and type of effects sought. Whenever feasible, he should take into account synergistic interactions among pollutants, influence of such cofactors as humidity, temperature, occupational exposure, and smoking habits, as well as the role of population characteristics, including age, sex, race, and state of health, in producing the observed effects. Accounting for meteorological factors is particularly important in the case of field studies, because wind, precipitation, humidity, and related factors play a major role in conveying pollutants to the plant and material subjects and in the damage mechanism.

Epidemiological studies may be longitudinal or cross-sectional. The former are more common and compare exposure and effects for a selected population in the same location over a period of time. Cross-sectional studies deal with similar population groups in different locations during the same period of time. These studies are more susceptible to misleading interference from extraneous factors that are more likely to vary with location than with time.

Epidemiological studies may also be classified as retrospective or prospective. Retrospective studies can be accomplished more quickly and are thus more common, but they force the investigator to make do with frequently inadequate available historic data. Prospective studies, on the other hand, involve future observations and afford the investigators some control over data collection procedures and format, but accumulation of the necessary data may take a number of years.

The great advantage of epidemiological and field studies over other approaches to assessment of the effects of air pollutants is the large number of available observations of both air quality and effects. This permits the identification of massive trends which are not as affected by random errors of observation and differences in population characteristics. The major drawback is the lack of effective control over the type, quality, and format of the data.

Clinical observations have the advantage of intensive, expert evaluation of health effects, but the data may not be readily accessible because of confidentiality, fragmented storage, and difficulty of retrieval. Moreover, the inherent selection of a population with clinical symptoms biases the sample toward the more susceptible groups and denies information on negative effects. This approach is most suitable for investigating the effects of occupational or other highly localized exposure.

Finally, it should be noted that epidemiological and field studies and clinical observations can only show an association between exposure to pollution and the observed effect, suggesting the existence of a causative relationship. Such a relationship can then be tested by toxicological or laboratory studies. It can be rendered plausible by the presentation of a reasonable connective mechanism, or other weight or reason.

3. Toxicological and Controlled Experiments

Toxicological investigations involve deliberate administration of controlled doses of specific pollutants to animal, and occasionally human, subjects and observation of the resulting effects. Other controlled experiments represent essentially the same approach for determining effects of pollutants on plants and materials. In all cases, the investigator can control the type and concentration of pollutant, exposure time and rate, composition of the population at risk, and the procedure for observing and recording effects.

Thus, in a typical toxicological experiment, selected inbred animals of uniform strain, weight, age, and sex are exposed to controlled amounts of pollutant for specified periods of time, and the resulting effects are noted and recorded. The experiment is repeated a number of times, with new populations and different exposures, until a definite relationship, or lack thereof, has been established. Toxicological experiments on human subjects are socially unacceptable in most instances, with the possible exception of low doses of the less harmful pollutants, such as carbon monoxide, photochemical oxidants, and sulfur dioxide, because of the relative mildness and reversibility of their effects.

A similar procedure applies in other controlled experiments involving plants and materials. Controlled experiments on the effects of oxidants and other air pollutants on plant growth and yield have been conducted in the field in side-by-side exposure chambers supplied, respectively with monitored ambient and filtered air. The more recent chambers are open at the top to admit rainfall and thus reproduce more closely natural conditions. Other investigators have assessed the effects of oxidants by spraying alternate crop rows with fungicides which protect the plants from ozone.

Because all conditions of the experiments can be strictly controlled, toxicological and other similar investigations are uniquely suited to prove the existence or lack of a causal relationship between dose and effect, In this sense, these investigations provide valuable supportive evidence to epidemiological and field studies.

On the other hand, pollution concentrations required to demonstrate these effects in the laboratory are seldom experienced in urban air, and it becomes questionable whether the results of such experiments are valid in assessing the effects of pollution exposure of the general population. Conversely, if the hypothesized effect is small, it may not be practical to test for it within the temporal contraints of a controlled experiment. Moreover, differences in physiology, life span, and dose rate make it difficult to extrapolate results from animal studies to human effects.

4. Surveys

Surveys can serve two important needs in assessing the effects of air pollutants: amplification of health effect data and reporting of less tangible effects. The typical tools of surveys are mailed questionnaires and personal interviews.

Amplification of health effect data typically involves learning about the background of a sample of people who died from a particular disease to identify implicated factors. Information of interest may include general state of health, smoking habits, and occupational exposure. In other cases, subjects of a morbidity investigation are requested to maintain diaries, where they note the occurrence and direction of any adverse symptoms. These surveys share many of the characteristics of epidemiological and field studies, except for the actual method of data collection.

Assessment of the less tangible aesthetic effects of air pollutants involves interviews to gauge changes in public opinion and behavior resulting from perception of impaired visibility, soiled surfaces, offensive odors, or smarting eyes. In addition to the common public opinion poll, some of the techniques for gauging these changes in opinion and behavior include estimation of willingness to pay for pollution reduction through the so-called bidding games and determination of losses in property values. This affords the rare opportunity of inferring a dose-effect function from an economic relationship. Unfortunately, surveys of public opinion and behavior are notoriously imprecise and provide at best only a qualitative assessment of the aesthetic effects of air pollutants. Proper education of the subject and minimal bias in the questioning can help to improve the validity of the results.

B. MEASUREMENT OF AMBIENT LEVELS

Measurement of ambient levels of pollutants, the first step in the development of a damage function, is complicated by the substantial variations of these concentrations in both space and time, diverse locations of receptors and monitoring instruments, inadequate sampling and measurement techniques, and inconsistent expression and aggregation of results. These problems are taken up here in turn, in preparation for the second step - determination of exposure, in the next section.

1. Formation of Ambient Levels

Ambient pollutant levels are governed by physical and chemical processes experienced by pollutants in the atmosphere under the influence of meteorological and topographic factors. The important considerations here are the nature of pollutant sources, the atmospheric processes, and their impact on air quality.

Pollutant emission sources may be classified on the basis of their mobility into stationary and mobile sources; on the basis of their size and shape, into point, line, and area sources; on the basis of their elevation,as ground-level or elevated sources; and on the basis of emission continuity, as continuous or intermittent sources. At times, however, some of these distinctions become blurred. Thus, emissions from a highway, normally considered a stationary line source, are actually contributed by numerous mobile point sources, and emissions from a number of home heating furnaces are typically lumped together as arising from a diffuse area source.

Upon leaving their respective sources, pollutants are subjected to a number of physical and chemical processes that are responsible for their transport, mixing, dispersion, and removal, as well as formation of secondary pollutants. The physical processes are governed both by meteorological factors, such as wind speed and direction, temperature distribution, and precipitation, and by topographic features, including mountains, valleys, and water bodies, as well as by human activities.

Temperature distribution in the atmosphere overlying the sources determines the mixing height - an effective ceiling, under which pollutants are mixed and dispersed by air turbulence. Precipitation cleanses the atmosphere by dissolving, adsorbing, or sweeping the pollutants and bringing them down to earth. The larger particles settle out on their own under the force of gravity.

Topographic features provide lateral containment or ventilation for the mixing layer. Impact of human activities on atmospheric processes is best illustrated by the so-called heat island effect. Large amounts of waste heat ejected by an urban area tend to set up a closed convection cell, in which air rises over the urban area, diverges outward in the upper layers of the atmosphere, descends over the adjacent rural areas, forming secondary pollutants, and finally converges inward in the lower atmospheric layers. In effect, the pollutants are trapped, converted, and recirculated within the metropolitan region, mixing primary pollutants from the city with secondary pollutants from the countryside.

Secondary pollutants are produced by chemical reactions in the atmosphere which are affected by temperature, humidity, and the sun's ultraviolet radiation. The more prominent reactions are the formation of photochemical oxidants by various combinations of pollutants, including nitrogen dioxide and hydrocarbons, oxidation of sulfur dioxide and nitrogen dioxide to the more hazardous nitrates and sulfates, respectively, generation of particutates by vapor condensation, and adsorption of gaseous pollutants on particulate surfaces.

2. Problems of Measurement

Attempts to relate ambient levels to pollutant emissions rely on analytical and statistical models of the various physical and chemical processes described above. Analytical models are based on a postulated and validated mathematical relationship between ambient levels and pollutant emission patterns, with meteorological and topographic factors as additional independent variables.

Statistical models, on the other hand, use historic data to relate observed ambient levels to various meteorological parameters, assuming that emission patterns remain constant. All of these models rely on certain critical assumptions about emission, meteorological, and/or topographic patterns. Their accuracy depends both on how well these assumptions hold for the situation at hand and on the availability of sufficient measurements to calibrate the model.

Because of the poor availability of historic emission data and the difficulty of applying analytical and statistical models, nearly all attempts at developing dose-effect functions have relied on measured values of ambient concentrations of specific pollutants. Such data have been collected since the late 1950's by the National Air Surveillance Network (NASN) and since 1962 by the Continuous Air Monitoring Program (CAMP). More recently, availability of air quality data has been bolstered by enactment of the Clean Air Act, which requires that each state measure and report ambient concentrations of total suspended particulates, sulfur dioxide, nitrogen dioxide, photochemical oxidants, and carbon monoxide. Both Federal and state data are supplied to the U.S. EPA National Aerometric Data Bank (NADB), where they are available for public use.

The key dilemmas in measurement of ambient levels are:

- Decision on precisely which pollutant species is to be measured
- Selection of the most appropriate analytical technique
- Location of the sampling and monitoring equipment
- Presentation of data.

The major pollutants investigated in development of the dose-effect functions reviewed in Chapter II and the corresponding studies are listed in Table 19. It will be noted that sulfur dioxide and particulates represent by far the most studied pollutants. A good illustration of the first dilemma listed above is presented by the measurement of sulfur dioxide and particulates as proxies for

Table 19. Pollutants Identified in Development of Dose-Effect Functions

Pollutant	Health Effects	Vegetation	Materials
Particulates, smoke shade, coefficient of haze, soiling index, dust	Buechley et al., 1973; Glasser and Greenburg, 1971; Hagstrom et al., 1967; Hodgson, 1970; Jaksch, 1973; Schimmel and Greenburg, 1972; Schimmel and Murawski, 1975; Silverman, 1973; Sterling et al., 1966, 1967, 1969; Winkelstein, 1967, etc.; Zeidberg et al., 1964, 1967		Beloin and Haynie, 1973; Booz, Allen and Hamilton; Campbell, 1972; Mattson and Holm, 1968; Michelson and Tourin, 1967; Robinson, 1972
Sulfur dioxide (SO_2), sulfates ($SO_4^=$)	Buechley et al., 1973; Durham, 1974; Finklea et al., 1975; Glasser and Greenburg, 1971; Hagstrom et al., 1967; Hodgson, 1970; Lave and Seskin, 1973. in press; McDonald and Schwing, 1973; Schimmel and Greenburg, 1972; Schimmel and Murawski, 1975; Sprey et al., 1974; Sterling et al., 1966, 1967, 1969; Winkelstein et al., 1967, etc.; Zeidberg et al., 1964, 1967	Bleasdale, 1973; Davis, 1972; Dochinger et al., 1972; Guderian et al., 1960; Hill et al., 1974; Linzon, 1966; Mansfield and Bull, 1972; Menser and Heggestad. 1966; O'Gara, 1922; Stone and Skelly, 1974; Temple, 1972	Aziz and Godard, 1959; Brysson et al., 1967; Gauri and Sarma, 1973; Guttman, 1968; Haynie, 1976; Haynie and Upham, 1970, 1971; Mattson and Holm, 1968; Sereda, 1960; Spence et al., 1974
Nitrogen dioxide (NO_2), nitric oxide (NO)	Chapman et al., 1973; Durham, 1974; Hammer, 1974; Lave and Seskin, in press; McDonald and Schwing, 1973; Pearlman, 1971; Shy et al., 1970, 1973; Sprey et al., 1974; Sterling et al., 1966, 1967, 1969	Hill et al., 1974; Stone and Skelly, 1974; Taylor and Eaton, 1966; Thompson and Taylor, 1969; Thompson et al., 1971	Salvin, 1972; Upham et al., 1974
Photochemical oxidants	Durham, 1974; Hammer, 1974; Hexter and Goldsmith, 1971; Sterling et al., 1966, 1967, 1969; Wayne and Wehrle, 1969	Barnes, 1972; Botkin et al., 1971; Brewer and Ferry, 1974; Costonis and Sinclair, 1969; Davis and Wood, 1972; Feder, 1970, 1972; Feder et al., 1972; Heagle and Heck, 1974; Heck and Tingey, 1971; Heck et al., 1966; Heggestad, 1973; Linzon, 1966; Menser and Heggestad, 1966; Miller, 1973; Thompson, 1975; Thompson and Kats, 1975; Thompson and Taylor, 1969; Thompson et al., 1972; Turner et al., 1972	Haynie and Upham, 1971; Salvin, 1972
Carbon monoxide	Anderson et al., 1973; Aronow et al., 1972, 1973, 1974; Hammer, 1974; Hexter and Goldsmith, 1971; Lave and Seskin, in press; Sterling et al., 1966, 1967, 1969		
Other (hydrocarbons, non-specific)	Anderson et al., 1965; Ferris and Anderson, 1964; Ferris et al., 1973; Lave and Seskin, in press; McDonald and Schwing, 1973	Kratky et al., 1974; Likens and Borman, 1974; McCune, 1969; McCune and Weinstein, 1977; Poovaiah and Wiebe, 1973; Swedish Royal Ministry for Foreign Affairs, 1972; Thompson and Taylor, 1969; Wiebe and Poovaiah, 1973; Wood and Borman, 1974	Baker, 1975; Dunbar, 1968; Greenlee and Plock, 1968; Van Rooyen and Copeson, 1968

sulfates, or perhaps some other unsuspected pollutant, once it became evident that SO_2 alone is not a major cause of adverse health effects. Investigators have turned to a number of additional indices related to particulate concentrations, such as smoke shade, coefficient of haze (COH), and soiling index. Finklea et al. (1975) went on to develop an empirical relationship between sulfur dioxide and sulfate levels.

The remaining three dilemmas are taken up in more detail in the sections that follow.

3. Methods of Measurement

A detailed discussion of the various methods of sampling and measuring the concentration of specific air pollutants is clearly beyond the scope of this report. However, the general characterization of these methods and of the attendant problems and errors is an essential element of the methodology for developing dose-effect functions. The principal characteristics of monitoring methods are:

- Sampling frequency
- Specificity
- Accuracy and precision, or reproducibility.

A sampling can be performed in either a batch-type or a continuous mode. The first mode involves sampling the air over a predetermined period of time and is followed by an analysis of the accumulated sample. This may be illustred by the high-volume sampler that collects particulates on a fiber filter, or the West-Gaeke-sulfamic acid technique for sulfur dioxide, which relies on bubbling air through an absorbent solution. The batch-type mode typically yields 24-hour average concentrations and obliterates diurnal variations.

The continuous sampling mode, illustrated by the chemiluminescent technique for ozone measurement, yields a continuous index of pollutant level. This output can be displayed on chart paper and digital readout units, or stored in a magnetic memory. Integration and averaging of these results over a preselected period of time can be accomplished with the aid of electronic circuitry.

Specificity and selectivity refer to the ability of a given method to measure the concentration of a particular pollutant in the presence of other, potentially interfering species. Accuracy, precision, and reproducibility reflect the proximity of replicate measurements to the true value and to one another. These considerations weigh heavily in the approval and acceptance by the U.S. EPA of the numerous measurement methods available.

The U.S. EPA has classified all air quality measurement methods into three categories: approved, unacceptable, and unapproved (neither approved nor unacceptable). At present, only the Federal Reference Methods (FRM) have been officially approved. These are described in appendices to 40 CFR Part 50, originally promulgated with the National Ambient Air Quality Standards on 30 April 1971. These appendices also introduced the concept of an "equivalent method", which provides that a method may become approved only by demonstrating equivalence to the reference method. (U.S. EPA, 1974).

The Federal Reference Methods for several pollutants are listed below:

- Total suspended particulates -- High volume sampler is the only acceptable method
- Sulfur dioxide -- The manual West-Gaeke-sulfamic acid (24-hour bubbler) method is the Federal Reference Method and other manual methods are unacceptable; continuous methods are unapproved
- Nitrogen dioxide -- The manual NASN bubbler method is considered unacceptable; all other methods are unapproved
- Photochemical oxidants (ozone) -- Continuous chemiluminescent method is the Federal Reference Method specific for ozone; a number of other methods for total oxidants are designated unacceptable
- Carbon monoxide -- The non-dispersive infrared (NDIR) is the Federal Reference Method; other methods are unapproved
- Total hydrocarbons (corrected for methane) -- Gas chromatographic flame ionization is the Federal Reference Method.

It should be noted that there are presently no acceptable techniques for measuring the very important pollutants nitrogen dioxide, nitrates, and sulfates, and indirect techniques subject to large errors and uncertainties must be used. In the case of a number of other pollutants, past techniques have been modified or altogether replaced, destroying the continuity of historic air quality records.

Errors in measurement of air quality are associated with both sampling procedures and analytical techniques. In the first instance, errors arise from inadequate control of the volume of air sample through malfunctions of pumps, flow meters, or other flow regulating devices, as well as from non-uniform retention in the filter or fluid. Error in analytic techniques can be attributed to human error, as well as to malfunctions of the analytic equipment.

4. <u>Location of Monitoring Equipment</u>

Adequate representation of ambient air quality requires both a sufficient number of monitoring stations and their judicious placement in the area under investigation. The first requirement is subject to budgetary constraints on the capital outlay for equipment and the costs of operation and data handling. Both tasks are necessitated and considerably complicated by the heterogeneity of the pollutant concentration field engendered by non-uniform emission patterns and atmospheric processes.

Studies of air pollution health effects revolve around available air quality data, but no metropolitan area systematically monitors all of the air pollutants alleged to affect health. Consequently, attribution of important health effects to certain air pollutants may well have been missed. As a case in point, recent investigations of the chronic health effects of nitrogen dioxide indicate that the national standard, established on the basis of very scant evidence, is substantially too high. (Sprey and Takacs, 1973).

Lack of sufficient monitoring stations is a very serious problem that has plagued nearly every investigation of effects of air pollutants. In urban areas, it has meant inadequate representation of exposure for the population at risk. The virtual absence of monitoring stations in rural areas has frustrated attempts to assess crop damage from recently discovered high levels of photochemical oxidants.

Common criteria for siting monitoring equipment are:

- Population density
- Absence of nearby or upwind pollution sources
- Accessibility, logistics, and security.

The first criterion calls for placement in the midst of the highest population density in an effort to reflect the ambient quality experienced by the greatest number of receptors. One major flaw here is that people are highly mobile. Another is that some pollution sources (e.g., automobiles or space heating) effectively move with people on a diurnal basis. Finally, this criterion cannot apply to secondary pollutants (e.g., photochemical oxidants, sulfates, and nitrates) which are formed through atmospheric processes, often at large distances from both the high population densities and the associated sources of primary pollutants.

The second criterion, concerned with improving representation of the measured values for the largest geographic area, calls for placement of the monitoring station away from automobile exhausts and stacks of power or industrial plants. This criterion is frequently in conflict with the first one, in as much as emission sources tend to coincide with high population densities, especially in the case of automobile exhausts.

Accessibility, logistics, and security usually turn out to be the most operative criteria, for obvious practical reasons. Typically, this implies a rooftop location, equipped with an elevator, sufficient electric power, and a lockable enclosure. Here again, the sensors are considerably removed from the great mass of receptors at street level.

In light of these conflicts, location of a monitoring station invariably represents a compromise, where some virtues are given up for the sake of others. Physical remoteness between sensors and receptors looms as the largest problem. On the other hand, recognition of a mistaken location does not solve the problem either, because moving the monitoring equipment to a more optimal location often involves the greater evil of losing continuity of historic air quality records.

5. Presentation of Data

Presentation of ambient air quality data involves a three-fold concern far data retrieval, aggregation, and display. Data retrieval is very much governed by the state of technology and budgetary constraints. State of aggregation is dictated in part by the nature of sampling equipment and by the intended use of the results. Display format should be guided only by the intended use of the results.

Until recently, monitoring data have been recorded by hand, or on strip chart devices, and considerable effort has been required to transfer such information to computer records. Automated systems now in use in some locations are capable of transmitting data directly to a central data acquisition and storage facility. The manual labor required to analyze chemically many samples and to review and verify recorded data has been so extensive that there exists a considerable backlog of inaccessible data, particularly in Federal programs. For example, detailed summaries of the National Aerometric Surveillance Network (NASN) observations reported by station are only available through the year 1968. The recent implementation of the Storage and Retrieval of Aerometric Data (SAROAD) dissemination programs by U.S. EPA is expected to improve this situation.

Because of the many problems in station operation and maintenance, existing data are often intermittent and of questionable accuracy. Over the years, comparatively little effort has been devoted to quality assurance of data and to the determination of equivalency for methods where methodology has been changed or equipment upgraded. The degree of uniformity in Continuous Air Monitoring Program (CAMP) data has been checked from time to time and the quality control of data from the California Air Resources systems is well documented. However, less than half of the present data available in the National Aerometric Data Bank (NADB) are considered valid an a national basis.

Aggregation of air quality results can be carried out on both a temporal and a spatial basis. In the first instance, the common units, beyond instantaneous or continuous readings, are hourly, daily, monthly, and annual averages, as well as the frequency or length of time that the measured values exceeded a given level, such as air quality standards. Assessments of acute effects associated with short exposures rely on hourly or daily averages, as well as on 90th or 99th percentiles of the daily averages, or on the frequency of violation of the short-term standard, over a period of one year. Chronic effects are more likely to relate to monthly or annual arithmetic or geometric means, or the length of time during which the long-term standard has been exceeded. Spatial aggregation of air quality data may take place over a city, county, or SMSA, over a region, such as an air quality control region, over a state, or over the entire country. Certain combinations of temporal and spatial aggregations are not very practical (e.g., state hourly averages or national daily averages).

Air quality data, as most other measurements, may be displayed numerically and graphically. Most gaseous concentrations are reported in micrograms per cubic meter of air ($\mu g/m^3$), or in volume parts per million (ppm), but other units have been adopted to suit specific needs. For example, settleable particulates may be measured in a dust fall jar as mass per unit area and time. Expression of pollutant levels as a fraction of the corresponding national air quality standard has been found useful by some investigators. Graphic representation of a pollutant concentration field over an area may take the form of equal concentration isopleths for a given set of meteorological conditions. Probability of occurrence of certain pollutant concentrations over a given area may be presented in the form of a "pollution rose" indicating frequencies of occurrence of various pollution levels.

C. DETERMINATION OF EXPOSURE

The exposure to air pollutants, which is responsible for the observed effects in a dose-effect study, is closely related to the ambient pollutant levels discussed in the preceding section. Here we take up the problems associated with this translation of ambient level into a measure of exposure. The material is presented under the headings of dose and dosage, mobility, shielding, and uptake, and measures of exposure.

1. Dose and Dosage

Exposure is typically measured as some formulation of ambient concentration levels and their duration, which may be expressed as a "dosage" or "dose". Dosage is the integral of the time and ambient concentration to which the subject has been exposed, while dose represents that fraction of the dosage that has been instrumental in producing the observed effect. In the case of health effects, this is the amount actually inhaled and retained, whereas. for plants and materials it is the portion that comes into actual contact with the susceptible surfaces. The direct measurement of dose is neither practical nor necessarily desirable for most. applications, as long as the same analog of dose, such as average or peak concentration and dosage, is used both in the formulation and interpretation of dose-effect functions.

An important concept in the determination of exposure is the dose rate, or the variation of concentration level with time. Acute effects and those characterized by a definite threshold level are produced when ambient concentration exceeds a certain level. In these cases, one is concerned primarily with the length of time during which ambient concentration exceeded that level. On the other hand, chronic and cumulative effects are likely to result from exposure at all concentrations, and here dosage is the more appropriate measure.

The commonly measured gross dosage is the integral of concentration and time recorded at the monitoring station. The difference between this quantity and dose may be accounted for by several important factors:

- Non-uniformity of the pollution field
- Mobility of subjects
- Shielding of subjects
- Uptake characteristics.

The first of these is concerned with likely differences in concentration between location of the sampling instrument and the subjects. The second factor refers to the daily commuting, weekend and vacation travel, and long-term migrations of the human population. The third factor deals with differences in ambient concentrations between the outdoors, where monitoring stations are located, and the indoors, where the building enclosure provides some shielding for the human population. Finally, uptake characteristics determine how efficiently the ambient concentration affects the subject.

Non-uniformity of the pollution field was taken up in the preceding section. The other factors are discussed below.

2. Mobility, Shielding, and Uptake

Exposure of stationary subjects, i.e., plants and most materials, is determined by the dynamics of the pollution field alone. However, for humans, animals, and other moving subjects, exposure is governed both by motion of the pollution field and by their own mobility. Human mobility takes the form of daily commuting and shopping trips between residential neighborhoods, commercial and industrial areas, and shopping centers, weekend and vacation travel to the less polluted countryside, and migrations to regions of the country promising greater opportunity,

Studies of air pollution health effects have frequently ignored the issue of human mobility, because there is no expedient way to assess its influence. Instead, it is frequently assumed that short-term mobility will help average out the non-uniformities in the pollution field, and that long-term mobilities are not too different among the various populations under study. The Federal Highway Administration has data on traffic zones between places or residence and employment for some 123 SMSAs which could provide some insight into this issue.

The need to consider the effect of shielding by building enclosures on exposure is underlined by the fact that an overwhelming portion of the U.S. population spends some 85 percent of its life indoors. This is especially true in the more polluted urban areas, although there is no information on the frequency distribution. Actually, indoor atmospheres may be more polluted in some respects, particularly in manufacturing and processing plants and in residences with faulty heating equipment.

The effects of various building enclosures on air quality have been investigated by Yocom et al. (1971) and Wade et al. (1974). Their salient conclusions were as follows:

- Indoor concentrations of particulates vary from 20 percent of outdoor concentration for public buildings in the winter to nearly 100 percent for private homes in the summer
- Large particles and the more reactive pollutants, such as SO_2, NO_2, and ozone are probably fairly well removed by building enclosures
- Carbon monoxide readily penetrates all structures
- Gas stoves contribute NO_2, NO, and CO emissions and raise indoor concentrations above those of the outdoors.

Uptake of air pollutants by humans and animals, on one hand, and plants and materials, on the other, exhibits important differences. The former, sometimes termed "active" receptors, bring pollutants in contact with the susceptible surfaces through inhalation and swallowing of the pollutant-laden mucus. Here the rate of uptake is a function of breathing rate, lung capacity, and nasal and ciliar defense mechanisms, and it remains fairly constant for an individual at a given level of activity.

Conversely, plants and stationary material objects are dubbed "passive" receptors, because pollutants are brought up and removed by external meteorological factors, such as wind and air, while humidity and temperature play a major role in the attack mechanism.

In this case, the rate of uptake depends not only on these meteorological conditions, but also on the attitude and texture of the susceptible surface and the presence of any protective mechanism, such as a vapor barrier formed by evapotranspiration from a leaf's surface.

3. Measures of Exposure

The three measures of exposure are various forms of concentration, dosage, and dose and their applicability depends on the type of pollutant and effect under investigation. In actual practice, several different measures may be tried and the one exhibiting the best correlation with the effects sought is selected. Moreover, it may be useful to construct composite indices, made up of several measures of exposure, that would yield an even better correlation.

The simplest measures, of course, are average concentration during a given period of time, or conversely, time at a given level of concentration. These are used typically in controlled experiments, where concentrations do not vary substantially.

The frequency, duration, and/or intensity of peaks or instances when ambient concentration exceeds a certain level are useful measures of exposure in conjunction with acute effects or effects characterized by a threshold value. An example of the latter is smarting of the eyes induced when the concentration of photochemical oxidants rises above a certain level.

Dosage, or the integral of concentration and time, on the other hand, is more applicable to cumulative pollutants, such as particulates or heavy metals, and to chronic effects, or ones characterized by a ceiling value. An example of the latter effect is the soiling of an exposed surface, the appearance of which does not deteriorate significantly, once an initial layer of crud has been deposited.

Direct measurements of dose are useful in explaining an attack mechanism and in documenting a causal relationship between exposure and effect. However, their use as a measure of exposure is neither practical nor desirable. Dose measurements do not lend themselves to massive studies, because they rely on examination of individual characteristics, and they are not readily translated into acceptable ambient levels, which is a common purpose of dose-effect studies. Thus, the relationship between dose and the actual measure of exposure selected for the study becomes implicit in the ensuing damage function.

The feasibility of conducting direct measurements of dose necessarily varies with pollutant and type of investigation. In toxicological experiments, dose can be measured by analysis of tissues of sacrificed animals, provided that the pollutant or its metabolites persist for a sufficiently long time and can be distinguished from other substances present. In human experiments, such measurements can be made for carbon monoxide by measuring the carboxyhemoglobin content in the blood, and for low doses of other pollutants, by comparative analysis of inhaled and exhaled air. In some cases, measurements are feasible with the aid of a radioactive label or other type of tracer mixed with the pollutant, or administered separately, if it shares the uptake characteristics of the pollutant.

In the case of plants and materials, particulate doses can be measured in terms of the total weight and size distribution of the deposited particles, although only a small fraction of these is likely to react with the surface before being blown off by the wind or washed off by the rain. The amount actually taking part in the attack can be measured by analyzing the plant tissues or the composition of the reacted surface layer of the material.